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FOREWORD

The Symposium on The Nucleus of the Atom and its Structure is the second symposium held by the Ohio State Chapter of the Society of the Sigma Xi, the first one having been on Metabolism. It is the aim of the chapter to present, from time to time as circumstances warrant, a series of lectures on some topic in science where the outposts of knowledge are being rapidly advanced, thus making new scientific material of great importance available to the general scientific reader.

This series on the nucleus is very timely because within the last three years numerous new fundamental entities and concepts have definitely evidenced themselves in nearly all experiments where the nucleus of the atom plays the major role.

The positive electron (or positron) was one of the first of the new entities to be discovered. The positron is similar, except for sign, to the commonly known electron; it was discovered late in 1932 in connection with experimental studies on the origin and nature of cosmic rays. Experiments on cosmic rays have been performed at a multitude of places on the earth, including the stratosphere. Professors W. F. G. Swann, Director of the Bartol Research Foundation and first speaker on this symposium, has with his colleagues contributed much to our present knowledge of cosmic rays.

Deuterium (heavy hydrogen) since its discovery has given to the physical, biological and medical sciences an ever increasingly useful and powerful tool. Many of the experiments performed recently owe their successful results to the larger quantities of deuterium made available by the few heavy water plants now in full operation. Professor H. L. Johnston has developed one of the very best plants in the country and has carried out many original experiments on this new isotope in its various compounds.

Artificial radioactivity, discovered last year by the Joliots, promises to be one of the really big steps in nuclear physics.

Already some 70 new nuclei have been synthesized and identified. A considerable development in the use of these radioactive nuclei as indicators for studying the behavior of their inactive isotopes is anticipated in the near future in the chemical, biological and medical fields. Professor E. O. Lawrence and colleagues at the Radiation Laboratory of the University of California have developed a four million volt cyclotron which has been notably successful in synthesizing a large number of these new nuclei.

Theoretical relations and new general principles are bound to follow in the wake of new discoveries. The beginning and development of the theory of nuclear transmutation processes owes much to Professor G. Gamow's contributions. The role of nuclear physics in astro-physical problems and in the theoretical origination of the chemical elements has also been given serious consideration by Professor Gamow.

The building blocks of matter, as we now know them, may change or be added to from time to time, but already our knowledge is quite extensive, although deficient in many respects. Undoubtedly then, it behooves all scientists to acquaint themselves with the essence of this knowledge so that they themselves may perhaps see an application of the new nuclear discoveries in their own special lines of endeavor.

F. C. Blake,
Chairman, Program Committee.

Editor's Note

Once again the Journal is pleased to be able to publish a series of Sigma Xi lectures on a timely and interesting topic. The prompt publication of these lectures in symposium form is made possible by the financial assistance and the editorial co-operation of the Society of the Sigma Xi.

L. H. S.

NUCLEAR PHENOMENA AND COSMIC RAYS

W. F. G. SWANN
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THE CHARACTERISTICS OF NUCLEAR ENTITIES

Meaning of the Existence of the Particles:—It is only a few years since physics hoped to correlate all the architecture of matter in terms of the ultimate properties of two entities, the electron and the proton. Now with a suddenness which is almost embarrassing, several other particles have been thrown into the arena and demand consideration in building the structure. Among the particles now available we have:

1. The electron.
2. The proton.
3. The positron.
4. The neutron.
5. The photon.
6. The deuton.
7. The hydrogen particle.
8. The alpha particle.
9. Nuclear entities of various kinds usually regarded as composed in some way of more fundamental entities 1. to 4.

In cosmic-ray matters, at any rate, entities 1 to 5 form the main field of our interest, although the more complicated particles do enter into the discussion.

When we are presented with an array of entities such as those referred to, and raise with ourselves the question as to whether or not certain of them exist in the nucleus of some atom, we are apt to encounter ambiguities of meaning founded upon whether some complicated particle such as an alpha particle exists in the nucleus as an individual entity, or whether it is to be thought of as made up out of such things as protons and electrons. We are confronted, for example, with the question of whether the proton is to be regarded as a neutron plus a positron, or as an entity distinct in itself. In some atomic transmutations we may raise the question as to whether some of the particles which we observe were in the nucleus originally or whether they were formed in the process of its disruption. These uncertainties of meaning become enhanced when we try to picture a structure for the nucleus. In classical theory we became confronted with the problem of putting into a nucleus of certain limited size a number of entities whose classical dimensions were so great that they would have to

overlap in order to accommodate themselves. In wave mechanical theory the various entities appear dissolved in a kind of mathematical fluid, from which any one may be precipitated at any desired moment for inspection by a suitable reagent which takes the form of a mathematical operation. Under such conditions it may not be out of place to pause a moment, from time to time, for the purpose of deciding with ourselves what it is that we are talking about, and in particular as to what meaning is to be attached to the statement that a certain entity, let us say a proton, is, or is not, inside a nucleus; and, if in the nucleus, as to whether it exists there as a fundamental entity or as something which is to be thought of as made up of two entities—for example a neutron and a positron. To my mind, definiteness of statement can only be secured along such lines as the following: When we wish to introduce into our problem such an entity as an atom, that atom has a certain mathematical representative which is responsible for all of its activities in the theory. That representative may be a Hamiltonian function. This function figures in some differential equations which are representative of the theory of the subject. In these differential equations are certain co-ordinates which are potentially representative of all of the entities which may figure in the discussion of all that may occur.[1] Any particular solution of these equations represent a *state* of the system. Some of the co-ordinates representative of certain entities may be absent *in any particular solution.* If such is the case, the entities concerned are absent in the state representative of that solution. It may be possible in the case of some particular solution, representative of a state, to make a transformation of co-ordinates in such a manner as to reduce the number of the co-ordinates. Then, entities characterized by the new co-ordinates may be said to exist in the state concerned.[2] Thus, suppose among the fundamental entities we had neutrons and positrons, but not protons. Then a free proton, or a proton in an electric field, for example, is to be considered as a system which, primarily represented by a function of the co-ordinates of a neutron

[1]The entities are supposed chosen so that they represent the minimum number necessary for telling the story of all that may occur through the agency of the accompanying mathematical theory.

[2]In this manner, for example, the co-ordinates of a suitable number of protons and electrons may, in certain cases, be mathematically welded into the much smaller number of co-ordinates of an alpha particle.

and a position, has been found, through a transformation of co-ordinates, to be represented by new co-ordinates to the extent of half the number. If, now, we raise the question of whether in an atom there are protons, or neutrons and positrons, the question at issue is whether the same transformation which reduced the number of co-ordinates in the single case of neutron and positron, above cited, will now function in similar manner to reduce the number of co-ordinates in the function representative of the state of the atom in question. If it does, we may say, by hypothesis, that a proton exists in the atom. It matters not whether some experiment reveals a proton as apparently ejected from the nucleus. The story of whether the said proton was, or was not, in the nucleus has no meaning except in the light of some definition; and the definition I have suggested seems to be the only obvious one available.

Significance of the Existence of Different Atoms:—While speaking of these rather general philosophical matters, one cannot resist the temptation to speculate a little further upon the significance of the quantum theory. At present we have a separate differential equation for each atom, the atom in question being characterized by the form of a certain function—the Hamiltonian function—entering into the equation. The different states of the atoms are characterized by the different solutions which are to be permitted as acceptable according to a certain criterion—the criterion of finiteness, single-valuedness, etc. May it not be that the different atoms themselves are to be regarded as representative of "quantum states" founded upon a yet wider idea of quantization. Many possibilities suggest themselves. Speaking generally, atoms of successively increasing atomic number are characterized, in part, mathematically, as systems of increasing numbers of co-ordinates. May it not be that there is one fundamental differential equation, or set thereof, involving, perhaps, in the initial instance an infinite number of co-ordinates, but of which only certain of the solutions satisfy the criteria demanded, finiteness, single-valuedness, etc., for example. It may be that all the solutions involving certain specified numbers of co-ordinates would be unacceptable. Presumably those involving more co-ordinates than are found in the heaviest known element would come into this category. The individual solutions in which the number of co-ordinates were limited would naturally satisfy, in addition

to the general differential equation involving the multitude of co-ordinates, certain special differential equations involving only the co-ordinates occurring in the solutions. Presumably these special differential equations would be those which we now think of as characteristic of the individual atoms.

Similarity of Different Particles for High Energy:—Another matter of significance concerns the respect in which the particles 1 to 9 really differ from one another. Of course the electron and positron differ from the neutron and photon in that they possess electric charge, and so have qualitative properties different from those of the uncharged entities. This is, however, only a special aspect of differences in properties such as one may think of as existing between the photon and the neutron, to which I shall presently refer. I wish for the moment to raise the questions involved in these particles in what we may call collision phenomena. The story of collision phenomena is governed, though not completely controlled, by two laws, conservation of energy, and conservation of momentum, which we may symbolize by considering a collision in which all the entities from (1) to (5), for example, are involved, and where, therefore, with subscript e for the electron, p for the positron, n for the neutron, P for the proton, and q for the photon, we may write

$$E_e + E_p + E_n + E_q + E_P = E_e' + E_p' + E_n' + E_q' + E_P'$$

where the dashed and undashed symbols refer to the conditions before and after the collision. Similarly, the conservation of momentum may be symbolized by the equation

$$M_e + M_p + M_n + M_q + M_P = M_e' + M_p' + M_n' + M_q' + M_P'$$

In these equations the various particles are characterized by the fact that, for particles (1) to (4) inclusive,

$$E = m_o c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right); \quad M = \frac{mu}{\sqrt{1-\beta^2}}$$

and for the photon,

$$E = h\nu; \qquad M = h\nu/c$$

Here the material particles are characterized by a rest mass m_0 and a velocity u, and the momentum of a particle is not expressible completely in terms of the energy. The quantum momentum is, however, completely expressible in terms of the corresponding energy, and indeed we may allow ν to evaporate

from the picture and simply say that the momentum of the quantum is E/c. It is of interest, however, to extrapolate the situation to velocities comparable with that of light, for which case m_0 is negligible compared to m. Thus, for example, in the case of an electron of a hundred million volts velocity, m_0 forms only half a percent of m; and, for such electrons and positrons as figure in the primary cosmic rays, m_0 forms only one part in twenty thousand, or less, of m. For protons of 10^{10} volts energy, m_0 still amounts to 5% of m, but for 10^{11} volts it forms only 0.5%. I wish to emphasize that at sufficiently high energies we may write for all of the particles, including the photons, M = E/c, and the equation of conservation of energy and momentum are completely summed up in two statements of the form

$$\Sigma E = \text{constant},$$

one vectorial, and the other scalar. All characteristics of the material particles and of the quantum have disappeared with the exception of the energy. A quantum and a proton of the same energy would behave in exactly the same way as regards what conservation of energy and momentum would have to say. Distinctions between the entities must now be sought on lines other than those having to do with conservation of energy and momentum. These distinctions commence to show themselves when we consider *experiments* to verify the predictions of the conservation of energy and momentum laws. Then the energy of the electron becomes something which is measured by a path deviation in a magnetic field, for example. The energy of a photon is something which is measured in a way which may be illustrated by the following example: Photons fall perpendicularly upon a hypothetical crystal grating. We confine our attention to those which come in some definite direction in relation to the grating. This direction defines for us the energy E to be assigned to the photon. You will see that I am thinking of the diffraction patterns produced by the photon; but I wish to suppress this idea in your minds, if you will permit me. I wish you to come upon it in another way. I wish to say that my measurement of the energy of the photon in terms of the angle of which I have spoken is, in the first instance, a matter of arbitrary definition; and, in the expression of the relation, an intermediate quantity $\lambda = hc/E$ comes in, or rather a series of quantities hc/E, 2hc/E, 3hc/E, etc.

They come in abstractly in determining the various angles at which the rays coming off from the grating correspond to the same energy. They are, of course, the wave lengths λ, 2λ, 3λ, etc., which figure in that picture of the phenomenon which regards everything as represented by a train of waves, of wave length λ, and of corresponding frequency $\nu = c/\lambda$, incident upon the crystal. From our standpoint the wave picture is not to be regarded as any real thing, but more as an artificial mathematical substructure analogous to Fourier's analysis, and the frequency ν is born of the primary concept of energy rather than the energy being born of the frequency ν. Relegating frequency to this abstract role relieves us of those apparent difficulties which arise in our minds when we try to picture a quantum simultaneously as a particle and as a wave spreading throughout the universe.

Then again a difference between the kind of particles, quantum, electron, etc., makes its appearance when these particles act as perturbating influences upon some atom, or where their energies are deduced on the basis of some theory of their absorption in matter. In such cases, the electron, for example, becomes introduced as a perturbing agent productive of a field of the kind we may associate with a moving charged particle, whereas the photon is represented as a periodic disturbance. In such fields as these the maximum of distinction prevails between the photons and the charged particles and the neutrons, but it is a distinction inherent in, and depending for its meaning upon, the theory of the processes assumed.

The foregoing remarks have been made not so much with the object of drawing any constructive conclusions from them, as for the purpose of cementing what appears to be the logical attitude towards them in any problem which concerns their nature. One constructive feature, however, following from the condition which all of these particles attain when the energy is sufficiently high, is a feature following from the fact that the energy is in all cases proportional to the momentum. The feature in question involves that in a collision between two particles of the same or of different kinds, one of which is initially at rest, the velocity after collision is in the same direction as that before. Thus, if the particle a collides with particle b, initially at rest, resulting in a supposed change of direction of a, we have, from the momentum condition

$$E_a = E_a' \operatorname{Cos} \theta_a + E_b' \operatorname{Cos} \theta_b ; E_a' \operatorname{Sin} \theta_a + E_b' \operatorname{Sin} \theta_b = 0$$

and from the energy condition

$$E_a = E_a' + E_b'$$

which demand for their consistency that Cos θ_a and Cos θ_b shall both be equal to unity. The feature is a very valuable one because it tells us that in the impact of very high energy cosmic rays with atoms so as to produce secondaries there is a perpetuation of the direction of the primary corpuscle so long as no energy goes into processes other than those involved in the laws of impact as specified.

Cosmic Rays

I must pass over introductory matters relating to the history of cosmic rays, methods of measurements, etc., and must take the matter up at the stage where we have to realize that a radiation of enormous penetrating power is entering our atmosphere. All the various particles which have been cited may be regarded as candidates for the position of cosmic rays. However, their credentials are different. Heavy charged particles such as alpha rays face the difficulty that all theories lead us to expect a very high absorption of such particles in the atmosphere, unless they possess an energy so high that their rest mass is negligible compared with their total mass. When this condition is satisfied, their rate of loss of energy by ionization alone depends only upon their energy and upon the square of the nuclear charge.[3] However, the energy which such a thing as an alpha particle must attain in order that its rest mass shall be as unimportant as that of an electron of the same energy is about 8,000 times the magnitude of that electron's energy. For such reasons alpha particles and heavy nuclei have not featured to any considerable extent as candidates for the position of primary cosmic rays, however great a part they may play in the subsequent activity, initiated in the first instance by the primary rays, and leading to atmospheric conductivity. However, such things as alpha particles, and particularly protons, are considered by more than one investigator as presenting reasonable credentials for consideration as primary cosmic-ray particles.

[3] I must here utter a word of warning based upon the fact that the crowding of the lines of electric force towards the equatorial plane perpendicular to the motion is a phenomenon depending upon the velocity rather than the energy. This phenomenon plays no ultimate part except when radiation reaction is considered. But, if it should play a part, then, to that extent, high energy particles of the same charge and energy would not be equivalent, regardless of their rest masses.

It is of course to be understood that practically all of the phenomena by which we observe cosmic rays are produced by secondaries. The cloud expansion chamber shows us an ample occurrence of phenomena in which relatively soft rays of only a few million volts velocity make their appearance, from some matter in the vicinity, sometimes in large groups, and obviously as the result of the initiation of some act by the primary rays. Occasionally from a mass of lead, for example, there will spring out bursts of rays, as many as five thousand in number. These rays do not appear to emanate from one point, but from several centers. Dr. G. L. Locher, at our laboratory, has given evidence for supposing that the primary center, where the burst initiates, emits neutrons among other things and that these neutrons serve as secondary initiators of the disruption of other atoms, so that the whole phenomenon spreads through the material, or throughout a portion of it, and so results in the very large bursts which are observed. We are at present conducting experiments along other lines and have a certain amount of evidence to show that bursts in one piece of matter can initiate bursts in others. This evidence is contained in an experiment carried out by Dr. and Mrs. C. G. Montgomery and myself. In this experiment we measured the bursts produced in the walls of an iron sphere which was suspended below a large tank of water so that the amount of water could be varied. It was found that the frequency of the bursts increased with the thickness of the water and then diminished with further increase. The increase of burst-production with increase of water is attributed to the stimulation of bursts in the iron sphere by the bursts produced in the water. The further diminution of bursts with increased thickness of water is attributed to a compensating action resulting from the absorption of the primary radiation by the water. The actual experiments showed an increase of 20% in the frequency of the bursts corresponding to 0.5×10^6 ions, for a water thickness of 79 cms. To remove the possibility that the apparent increase of number of bursts in the sphere represented simply a measurement of spurts of ions produced in the sphere by rays which had come directly from the water, the iron sphere was replaced by a magnesium sphere, and the experiments were repeated. Any effect produced by the direct action of the rays from the water, without intermediary action in the walls of the sphere, should show itself just as well for the magnesium sphere as

for the iron. However, no increase in burst frequency was found by increasing the thickness of the water when the magnesium sphere was used.

The fundamental significance of this experiment is that it substantiates the opinion expressed by Dr. Locher to the effect that a number of atoms participate in the production of the bursts. This gives us some relief from the difficulty inherent in the fact that the total energy required to produce some of these bursts is greater than the energy which could be reasonably expected to be liberated in one act in any atomic process which we know of, including the complete annihilation of heavy atoms. It also weakens considerably the claims of a rival theory which has been put forward to account for the origin of these bursts, and which, in view of its dramatic nature, I must not pass by without mentioning. Recent developments in atomic structure and the theories thereof have come to a realization of the possibility of the disappearance of matter and the accompanying appearance of radiant energy in proportional amount. They have also envisioned the reverse process in which radiant energy can be converted into material substance. The general idea of the production of these bursts inherent in the theory to which I have referred is to the effect that radiant energy in the form of a photon cosmic ray descends upon the substance under test. Occasionally such a ray comes into violent contact with the nucleus of an atom. Under these conditions it is supposed that nothing in particular happens to the atomic nucleus, but that the photon becomes mathematically irritated in such a manner as to cause it to decide to change its existence, commit suicide, and become resurrected as a group of particles. If you should ask for a crude analogy, I suggest that you think of a spiritualistic seance. The photon is the ghost, the shower of particles is the materialized ghost, and the atom is the medium.

There is sometimes even an indication of a delay between the different portions of an atomic burst. Fig. 1 shows a galvanometric trace on moving photographic paper showing a burst at the point marked by the arrow. The burst is recorded as ionization in a closed chamber; but, as a check, a system of counters was distributed about the chamber so as to record these bursts by other means. The sharp lines indicate the discharge of the counters and it is obvious that we have here two discharges separated by a distance of what amounts to about

one second, and which seem closely associated with the complete bursts as recorded by the galvanometer. It is perhaps too early in view of the limited number of such cases to say that we have here an illustration of induced radioactivity brought about by cosmic rays, but the result indicated is at least significant, particularly when it is remembered that, with the arrangement of tubes used the chance of two random discharges coming as close together as these is negligible.

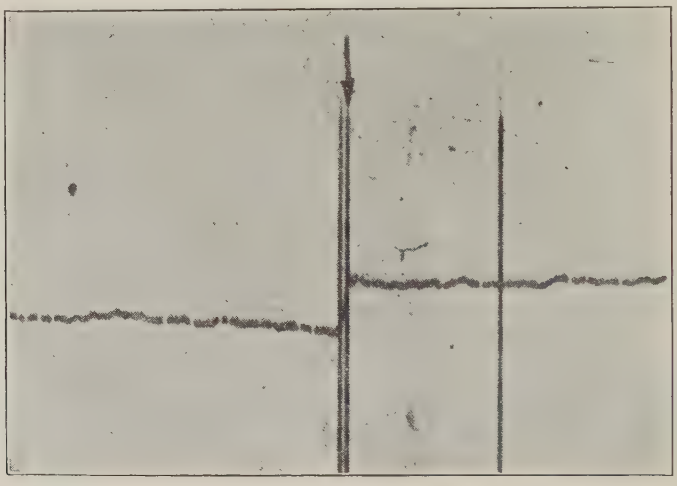
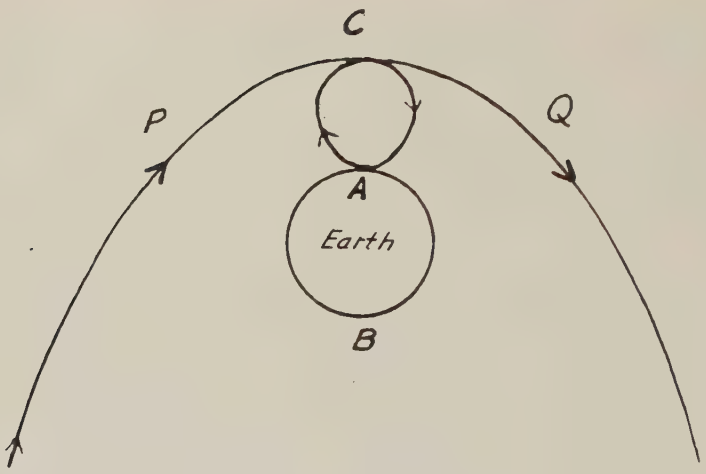


FIGURE 1

The Exponential Law of Absorption:—It has, of course, been known for many years that what is now called the cosmic-ray intensity varies with altitude in a manner which is approximately described by the supposition that the radiation is absorbed according to an exponential law. Now the hypothesis that the primaries are composed of photons of definite frequency lends itself reasonably readily to the explanation of such a law. The characteristic possessed by photons which is of significance in this connection is that of passing through matter without the continual loss of energy in small amounts, the energy losses being confined to amounts comparable with the whole energy of the photon, but taking place only rarely. Under such conditions the intensity of the radiation is governed by the laws of chance in relation to the distance travelled, just as chance determines the density of a stream of bullets at different distances from a machine gun, when the machine gun is fired

into a forest. On the other hand, charged particles, at any rate those of energies comparable with those met in former investigations, lose energy continually in passing through the air, the individual energy losses amounting to insignificant fractions of the total energy of the ray concerned. Under such conditions the rays have a definite range. A parallel beam of rays suffers no change of intensity as measured by the density of the rays until the distance is reached at which its intensity falls to zero. Thus, at first glance, at any rate, the hypothesis of charged corpuscles is entirely unsuited to the explanation of the exponential law of absorption. Until comparatively recently, moreover, the hypothesis of charged particles was ruled out on the basis of the effects which they would imply as the result of the action upon them of the earth's magnetic field.

Evidence of Charged Particle Primaries:—The earth's magnetic field is a very potent agent in controlling the activities of charged particles which seek to approach our earth. The earth's field is weak but its extent is great, so that at the equator an electron must have from one to six times ten thousand million volts energy depending upon the direction in order to reach the equator. The energy necessary for entering becomes less and less as we proceed toward the poles. The orbits of the electrons assume extraordinarily complicated forms. The smaller the energies of the rays, the more easily are the paths bent. Many years ago, the Norwegian physicist, Carl Störmer, suggested that the Aurora Borealis might be caused by electrons emitted in this case with great energy from the sun. The effect of the earth's magnetic field upon these electrons would be to cause them to move toward the polar regions. The smaller the energy, the more would be the bending of the electrons' paths in such manner as to cause them to enter the atmosphere near the poles; and, even to get the aurora to exhibit itself, on such a theory, at latitudes as low as that at which it is found, Störmer found it necessary to attribute to the electron energies a thousand times greater than any which had been encountered in the laboratory at that time. In those days such an assumption was regarded as very speculative. The mathematics of this subject is contained in its essential elements in the work of Störmer, done some twenty years ago. However, the subject has received a renewed interest in the light of modern developments in connection with cosmic rays. It has been convenient to consider certain specific matters



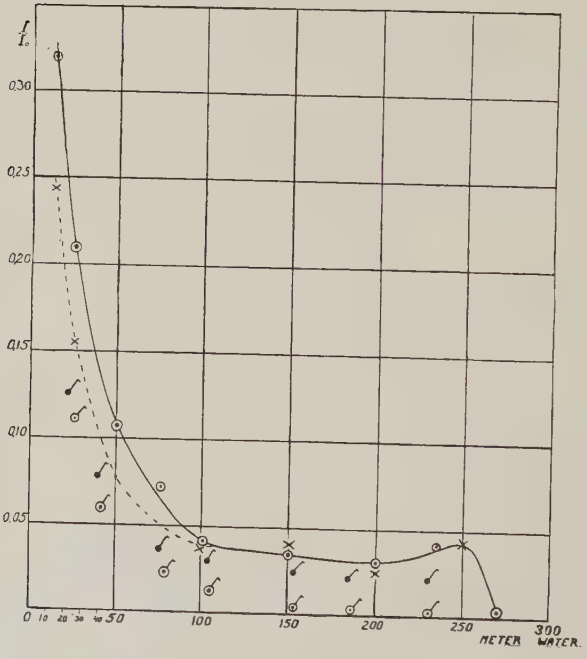


FIGURE 2 (Upper)
FIGURE 3 (Lower)

sometimes as generalizations of, sometimes as special cases of Störmer's theory, and sometimes by special calculations made *ab initio*, with the immediate end in view. Ten years ago, I showed by calculation that an electron with an energy so large that a thousand million volts would be necessary to give it that energy, would not be able to approach the earth in its equatorial plane nearer than to eight times the earth's radius, without being turned back into space. To reach the earth's surface at the equator, an electron must have an energy at least equivalent of that attained under a potential difference of ten thousand million volts. Even under these conditions, as I pointed out about three years ago, the electron which just succeeds in reaching the earth at the point A, Fig. 2, travelling in the magnetic equatorial plane, does so by describing a complete loop. It is easy to see why the electron describes such a loop. You might think that an electron coming from the lower half of the diagram and approaching the earth, would try to reach it at some point such as B. However, as the electron approaches the earth, the earth's magnetic field demands that the path of the electron shall bend, and continue to bend. In order to be able to obey the earth's magnetic field and yet reach the earth, the electron describes the orbit PCAQ shown in Fig. 2. By looping the loop completely, it is able to secure the maximum amount of bending in obedience to the earth's magnetic field, and indeed actually makes use of this bending to come back and touch the surface of the earth before it returns to space.

Now my purpose in showing Fig. 2, is to call to your attention the complicated nature of the orbits of electrons approaching the earth. Störmer spent very many years in calculating these orbits; and, indeed, they can not be calculated by elementary processes of mathematical procedure. Many of them twist about and curve all over the place in most fantastic manner. Under these conditions one might suppose that if an appreciable fraction of the primary cosmic rays was composed of electrons, there would be a very great variation of cosmic-ray intensity with latitude, in view of the fact that it is easier for the electrons to get in at the poles than at the equator. Since until recent times no such variation with latitude was known, it was customary to assume that no appreciable fraction of the primary rays could consist of charged particles. Then three or four years ago, J. Clay in Europe and A. H. Compton and his

associates, in a world survey, found a definite variation with latitude, but of a rather peculiar nature. For latitudes north or south of 34°, there was very little variation. For latitudes lower than 34°, there was a diminution in cosmic-ray intensity which amounted to 14% of the equatorial value at sea level, and to as much as 33% at an altitude of 4,300 meters. Such a condition was at first very difficult to understand. Then it was shown by Lemaitre and Vallarta that if a certain mathematical theorem concerned with the motion of the electrons in the earth's magnetic field could be regarded as true, the story of the cosmic-ray intensity, although extremely complicated in the actual details concerned with the orbits of the electrons themselves, should show remarkable features of simplicity as regards the intensity itself. It turned out that if the theorem to which I have referred was true and if the cosmic rays were uniformly distributed in direction in outer space, then, while their paths would be enormously distorted as they approached the earth, they would be distorted relatively to each other so that the number of rays coming through a cosmic-ray telescope pointed in any direction would have the following characteristics. At any assigned place, and for any one energy of ray, *either* the number would be exactly the same as it would have been had there been no magnetic field, in spite of the fact that the direction of these rays, if produced backwards outside of the earth's atmosphere to remote distances would there have nothing like the directions which they would have had in the absence of the earth's magnetic field, *or* the number would be zero. There could be no compromise. Either the electrons came in with the normal intensity or they did not come in at all. The truth of the mathematical theorem to which I have referred was first sensed by Lemaitre and Vallarta. It was found subsequently to involve principles rather more subtle than had first been supposed, but later by a more rigorous mathematical treatment of the subject I was able to establish the truth of the theorem in a manner which I believe is regarded as satisfactory even by those who have doubts concerning the complete story of the Lemaitre-Vallarta theory itself. The significant elements of the Lemaitre-Vallarta theory may be illustrated in the following way. Suppose that we confine our attention to electrons of any one energy, and, let us say, of positive sign. Then, in general, if we should take our stand at any

particular latitude on the surface of the earth, there would be, for any assigned electron energy, a certain cone with its axis of symmetry tangential to the earth and pointing due west. Within this cone no rays of the assigned energy would enter. Outside of it, the rays would enter with the normal intensity. As we moved towards the pole, the cone would become narrower in angle; and, at some latitude sufficiently high, would become so narrow as to close up completely, so that, at this latitude, there would be no direction from which rays of the assigned energy could not enter, and the same may be said for all higher latitudes. Going back to our starting point, however, and moving towards the equator the cone would widen up in angle so that the direction from which rays could not approach would comprise more and more of the sky. If the assigned energy of the electrons were sufficiently small, the cone would widen up to such an extent as to turn inside out and cover the whole of the sky. Under these conditions no rays of the energy concerned would reach the point in question from any direction whatsoever. On the other hand, if the energy were sufficiently high, the cone of exclusion would narrow down to a small angle, even to zero angle at the equator itself, so that here and everywhere else on the earth, rays of this energy would enter from all directions.

This story of the cone contains the story of the variation of the total cosmic-ray intensity with latitude, and it also contains the story of the difference between the intensity from the east and from the west for any given latitude. If all the rays had one single energy and all carried the same sign of charge, say positive, the story of the difference between the intensity from the east and from the west would be very simple. If we were at a place where the cone of exclusion existed at all, there would be no intensity from the west and the full intensity from the east. In general, this story is complicated by the existence of a wide range of energies for some of which there is an exclusion angle and for some of which there is not. It is also complicated by the possibility of there being charged particles of both signs. It is obvious that if charged particles of both signs existed in equal amounts there would be no difference in intensity from the east and from the west, although there would, of course, be a reduction in each of these intensities. The whole story of these latitude and directional effects is rather complicated, and I must not enter into it in detail. It

must suffice to summarize the main facts.[4] By experiments carried out by T. H. Johnson and J. C. Street on the top of Mount Washington in the summer of 1932, the existence of an east-west asymmetry was verified and the observations were such as to indicate that the charged particles responsible for the effect were charged, preponderatingly, positively. These results were confirmed and extended by the work of T. H. Johnson, and independently by that of L. W. Alverez and A. H. Compton in Mexico. Since that time Johnson has extended the observations to a wide range of altitudes and to equatorial latitudes. Combining the results of the experiments on the latitude- and directional-effects, we may then conclude as follows:

(1) The latitude intensity measurements of A. H. Compton and his associates give, from the sea level measurements, a diminution of 12 per cent[5] of the cosmic ray intensity in passing from high latitudes to the equator. For measurements at high altitudes, the corresponding change is 25 per cent.[6]

(2) The radiation of corpuscular nature which carries a positive charge is in excess of that carrying a negative charge.

(3) By combining the latitude variation in intensity, which depends upon the sum of the negative and positive corpuscular currents, with data on asymmetry, which are determined by the difference between these currents, T. H. Johnson is able to determine how much of each sign of current is involved. Confining attention to the sea level data on the latitude effect,

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[4]For those who are unacquainted with the subject it must be remarked that relative intensities in different directions are obtained by an appliance which we may call a cosmic-ray telescope. A Geiger-Mueller counter comprises a hollow metal cylinder with a wire passing along the axis, the whole device being enclosed in glass and containing gas at reduced pressure. If the potential difference between the wire and the cylinder is adjusted to the right amount, the passage of a cosmic ray through the cylinder precipitates a discharge which may be amplified and recorded by suitable means. Suppose that three of these counters are arranged with their axes parallel and their centers on a line perpendicular to the axes, and suppose that the amplifying and recording mechanism is such that the final record is made only if all the counters discharge at once, then it is obvious that the system constitutes a cosmic-ray telescope which measures only those rays which come in such directions as to cause them to pass through all three cylinders.

[5]The 14 per cent quoted by Compton is expressed in terms of the intensity at the equator. A similar remark applies in the case of the 25 per cent cited later, which corresponds to Compton's 35 per cent of the equatorial intensity.

[6]It must be remarked that this 25 per cent and the 12 per cent cited above do not constitute a discrepancy. Both are lower limits, and the high altitude data give the larger value because they are more sensitive to the corpuscular nature of the rays, since they involve lower energy rays which have not been absorbed or had their potency for measurement reduced by the lower regions of the atmosphere.

it results that practically all of the corpuscular radiation which corresponds to energies sufficiently low to show a directional effect is of the positive type. While this result is not as inevitable when based solely upon the less accurate high altitude data for the latitude effect, it is in agreement with those data within the limits of their accuracy.

(4) The latitude effect gives us a lower limit for the amount of the corpuscular radiation. However, the limit obtained in this way does not include any corpuscular radiation of such an energy as can reach the earth at the magnetic equator. On the other hand the existence of an asymmetry at the equator enables one to add to the lower limit an additional corpuscular current. The net result is still only a lower limit, because it does not include any corpuscular current of energy so high that it would show no asymmetry effect at the equator. Proceeding according to these principles, and expressing percentages in terms of the total radiation of all kinds as measured at high latitudes, T. H. Johnson has been able to add 4.5 per cent to the 12 per cent resulting from A. H. Compton's latitude measurements at sea level. This would lead us to conclude from the sea level observations alone that at least 16 per cent of the intensity as measured at high latitudes is of the charged corpuscular nature. However, if we confine measurements to those at high altitudes, Dr. Johnson finds that the equatorial asymmetry data demand a minimum contribution of 6 per cent to the high latitude, high altitude intensity; and A. H. Compton's latitude measurements give a contribution of at least 25 per cent, so that these high altitude measurements demand a total contribution of 31 per cent as the minimum charged corpuscular contribution to the radiation.

The 31 per cent demanded for the corpuscular contribution is sufficient to "spoil" the exponential law provided so readily by the photon hypothesis unless the corpuscular hypothesis can itself be adapted to give that law. With the necessity of this adaptation facing us, it then naturally becomes of interest to see how far we can account for all of the cosmic-ray phenomena on the hypothesis that the primaries are of a corpuscular nature.

Difficulties Involved in Corpuscular Hypothesis:—According to the most naive views, the exponential law would have to be provided for in the corpuscular theory by the existence of a wide range of incoming corpuscular energies which penetrated

the atmosphere to different depths depending upon the energies of the individual rays concerned. The amount of radiation to be found at any depth below the top of the atmosphere would depend upon the number of incoming particles which happened to exist in the energy ranges necessary to reach the depth concerned; and the existence of an exponential law of absorption, or, if you prefer, of intensity with distance traversed, would necessitate the assumption of a special type of energy distribution in the incoming particles necessary to secure that law. Even though we accept the necessary assumptions, however, a great difficulty remains. For under the simple conditions postulated it would turn out that the quality of the radiation would be the same at all altitudes. By this I mean that if at sea level, for example, we should find a certain distribution of energy among the rays, then at higher altitudes one would find the same relative distribution. The number of rays having any given energy would be greater at the higher altitude; but rays of all energies would be greater in the same proportion. At first sight this result is contrary to our intuitions and is contrary to what has presumably been generally believed; for it is natural to argue that the rays at high altitude would contain a preponderatingly larger proportion of low-energy rays than would those at low altitudes, because the low-energy rays cannot penetrate to low altitudes. We must remember, however, that the rays which possessed high energy at high altitudes will, by process of absorption, become rays of low energy at low altitudes. They exist at low altitudes not because of the energy which they *have* there, but because of the energy which they *had* before they got there. If all of these matters are taken into account, then, as I have shown elsewhere, providing that one assumes the distribution of energies in outer space necessary to give the exponential law, it follows, as an inevitable consequence, that the quality must be the same at all altitudes.

Now the experimental data at our command resist, absolutely, harmonization with the view which concludes that the quality shall be independent of the altitude; for, upon such a view, the number of atomic bursts from lead, for example, would increase with altitude exactly in proportion to the measured number of cosmic rays themselves. Now such a conclusion is drastically contrary to some recent experiments of C. G. and D. D. Montgomery upon the frequency of these

bursts at high altitudes. For the Montgomeries have found that whereas the cosmic-ray intensity increases by a factor of five from sea level to the summit of Pike's Peak, the frequency of the atomic bursts increases by a factor of twenty-five. Similar results have been found by R. D. Bennett, G. S. Brown and H. A. Rahmel. Further, analogous conclusions follow from the experiments of T. H. Johnson and of B. Rossi and S. de Benedetti, upon small showers of secondary cosmic-rays produced by the primary cosmic radiation. Again recent measurements carried out in stratosphere flights[7] with Geiger counter apparatus designed by G. L. Locher and myself, when combined with data on the increase of intensity with altitude as measured by ionization chambers, have shown that the ionization produced by the rays in a closed vessel increases more rapidly with altitude than does the intensity of the rays itself, indicating once more a change of quality with altitude.

A New Form of Corpuscular Theory:—In order to overcome these difficulties, and at the same time secure the exponential law in what seems to be a more natural way, I have been lead to formulate a view as to the mechanisms of the processes involved which, in its simplest aspect, and to a first approximation, takes the following form. Let us suppose that primary rays of a single energy enter the atmosphere uniformly in all directions and that, as they travel through the atmosphere, they produce along their paths secondary rays possessing energies such as those which figure in cosmic-ray phenomena, but smaller than the energy of a primary ray. The secondary rays may be produced directly, or through a photon as intermediary. Let us suppose that these secondary rays are the chief entities which are observed in our cosmic-ray counters, and that they perpetuate the direction of the primaries which produce them. This last-named characteristic is hardly an assumption since it follows, as I have already shown, from the laws of impact in which both the primary and secondary particles have very high energies. In addition to this we shall assume, and this is the vital assumption, that the loss of energy per cm of path is proportional to the energy of the primary ray. Or, in other words, we shall assume that the number of secondaries per

[7]The first of these flights was made by Major W. E. Kepner, Capt. A. W. Stevens and Capt. O. A. Anderson. The second was made last fall by Prof. and Mrs. Jean Piccard.

cm of path is proportional to the energy of the primary. It is then clear that, even though all the primaries come right through the atmosphere so that the number of them passing through a square centimeter is the same at all altitudes, the measured effect, depending as it does upon the number of secondaries, will increase with altitude because of the increase of primary energy with altitude. When we submit the matter to calculation we find that the intensity as measured by the number of rays follows exactly that law which we have called the exponential law.

For, if the number of secondary rays produced per centimeter of path of the primary is proportional to the energy of the primary, then, if the secondaries perpetuate the paths of the primaries, the number of secondaries n_θ per unit area per unit solid angle corresponding to any zenith angle θ is

$$n_\theta = \alpha E \tag{1}$$

where E is the primary energy and α is a constant.

If the primaries lose energy entirely by the creation of secondaries, and if dx is an element of path of the primaries, and β a constant,

$$-\frac{dE}{dx} = \beta n_\theta = \beta \alpha E \tag{2}$$

So that

$$E = E_o e^{-\beta \alpha x} \tag{3}$$

Moreover, in view of (1)

$$n_\theta = (n_\theta)_o e^{-\beta \alpha x} \tag{4}$$

Again, (3) and (4) show that the apparent coefficient of absorption of the rays is independent of their energy, so that, without disturbing the exponential law, it is possible to permit the primary rays to possess a wide range of energies, and thus to remove one of the postulates which, at first sight, it might seem necessary to make. All energies give, in fact, an exponential law with the same coefficient of absorption.

The main feature of the foregoing theory is that, in it, the exponential law of absorption is secured as the result of the mechanisms of the processes taking place in the atoms, the emission of secondaries, and does not rely upon some peculiar distributions of energies among the incoming rays. Again, having secured now a variation of quality with altitude, we are well prepared to see in a natural way how such experiments as

those of the Montgomeries can be accounted for. Thus while we suppose that the law of production of secondary rays from the *air* is one which makes the number produced under assigned conditions proportional to the energy of the primary rays, let us suppose that in the case of *lead*, the rate of production of those secondaries which we call cosmic-ray bursts is proportional to a higher power of the energy than the first. Suppose, for example, that doubling the energy of the primary rays gives us four times the number of bursts. Then it is easy to see that, as in the case of the experiments of the Montgomeries, if the measured cosmic-ray intensity increases by a factor of five from sea level to the top of Pike's Peak, the number of bursts will increase by a factor of twenty-five. Moreover, in a more detailed form of the theory, we may well expect that the nature of the secondary rays produced from air will depend to some extent upon the energies of the primaries. In fact, the secondaries themselves may, in certain cases. arise not directly from the primaries but through the intermediacy of photons produced by the primaries, which photons in turn eject the electrons as secondaries from the atoms of air. There is thus ample provision for the situation found in which the ionization in a closed vessel varies with altitude in a manner different from that for the intensity of rays as measured by counters, since the ionization is produced by the secondaries and even by other entities, as neutrons, etc., which may be liberated by the primaries.

It will be observed that the foregoing simple theory makes the coefficient of absorption of the energy the same as that of the measured intensity, when the intensity is measured by the numbers of the secondary rays. This fact is of interest because it suggests between the energies of the rays entering the atmosphere and the energies as measured at sea level, a relation calculable in terms of the relation between the cosmic-ray intensity at, or near, the top of the atmosphere and the corresponding intensity at sea level. The recent stratosphere flight made by Major W. E. Kepner, Capt. A. W. Stevens, and Capt. O. A. Anderson, and also that made by Professor and Mrs. Jean Piccard, both with Geiger counter apparatus designed by G. L. Locher and the writer, agree in showing that the vertical intensity, when extrapolated to the top of the atmosphere, is about 90 times the sea level value. The minimum electron energy necessary to permit vertical entry

in opposition to the earth's magnetic field in these latitudes, is about 4.5×10^9 volts. The corresponding sea level value would consequently be about 5×10^7 volts. This is a reasonable value in the light of the requirements demanded of it. The energy necessary for vertical entry at the equator is about 3×10^{10} volts, and if we could assume the same law of increase of intensity with altitude at the equator as at these higher latitudes, the corresponding minimum sea level energy for the primaries would be about 3×10^8 volts. Of course, these are only *minimum* values for the energies of the vertical rays, and higher energies at entrance will correspond to higher sea level energies. Apart from any other considerations, however, the principle here exemplified is sufficient to explain why cloud chamber experiments made, of course, at low altitudes, have failed to reveal corpuscular energies as great as those which would be suggested by consideration of the requirements of the earth's magnetic field. Moreover, consideration of these matters serves to emphasize the importance of cloud chamber energy measurements at high altitudes.

An element of difficulty exists from a consideration of the case of rays which are inclined appreciably to the vertical, and which at entry are of sufficiently low energy to show azimuthal asymmetry. These rays, traveling as they do through distances in the atmosphere considerably greater than the vertical rays, would be expected to become reduced in energy at sea level to values below those permissible for the performance of their functions. This difficulty tends to disappear in a more complete formulation of the theory to which brief reference will now be made.

Extension of the Theory:—While the foregoing simple form of theory correlates the more immediately obvious phenomena, it requires modification in detail. That very feature which gives the power to predict an exponential law—the feature which causes the percentage rate of absorption of energy to be independent of the energy—is one which, in its exact form, denies a fact characteristic of the azimuthal asymmetry effect, the fact that the percentage asymmetry increases with altitude. For this increase with altitude means that the primary rays which are responsible for the asymmetry, and which are therefore the rays of least energy, have a greater apparent coefficient of absorption than that which corresponds to the average radiation. In other words we must admit an increase of absorbability with

decrease of energy. Such a provision may be made purely empirically. Thus, if (1) be modified to the form

$$n_\theta = \alpha E^{1-\lambda} \tag{5}$$

where λ is a constant, (2) assumes the form

$$-\frac{dE}{dx} = \beta\alpha E^{1-\lambda}$$

and, if we define the coefficient, μ_e of absorption of the energy at any point as $-(1/E)\ (dE/dx)$, we find

$$\mu_e = \beta\alpha E^{-\lambda}$$

We are concerned more particularly with the measured coefficient of absorption μ_n, defined as $-(1/n_\theta)\ (dn_\theta/dx)$. In view of (5)

$$\mu_n = (1-\lambda)\ \mu_e$$

so that on the basis of the hypothesis under consideration, both μ_n and μ_e increase with decrease of energy.

The result may be secured in another way, having a more direct physical significance. For if, leaving (1) unchanged, we replace (2) by

$$-\frac{dE}{dx} = \beta n_\theta + \gamma \tag{6}$$

the quantity γ represents a constant loss of energy per centimeter of path all along the path of the primary. It is symbolized, for example, by such a loss as is represented by ordinary ionization.

Combining (1) and (6) we thus obtain

$$\mu_e = \beta\alpha + \gamma/E \tag{7}$$

and observing from (1) that $\mu_n = \mu_e$, we have

$$\mu_n = \beta\alpha + \gamma/E$$

which again gives an expression which causes μ_n to increase with decrease of E.

It is of interest to observe in general that if (1) be modified to

$$N_\theta = \alpha E^s \tag{8}$$

$$\mu_n = s\ \mu_e$$

so that if s is greater than unity, μ_n is greater than μ_e. Such a provision has an advantage in causing the ratio of the energy

of the rays entering the atmosphere to the energy of the rays at sea level to be less than the ratio of the corresponding measured cosmic-ray intensities. This consequence lessens the difficulties already referred to in the matter of the asymmetric rays, concerning the entering energies as computed from the earth's magnetic field, and the sea level energies as computed from the entering energies and the coefficient of absorption.

The incorporation of (8) into the theory as represented by (6), leads to

$$\mu_e = \beta a E^{s-1} + \gamma/E$$

and

$$\mu_n = s\beta a E + s\gamma/E$$

This expression represents a μ_n which increases with decrease of E for low values of E, but which decreases with decrease of E for high values of E.

A further remark must be made concerning the fact that in so far as there is a departure from the exponential law of absorption in the atmosphere, that departure is in the direction of a hardening of the rays as they approach the earth. At first sight this fact is contrary to the principle that the effective coefficient of absorption of the rays increases as the rays lose energy—a principle demanded by the asymmetry effect. The difficulty is only transitory, however; for, now, we introduce once more the idea of a wide range of primary energies entering the atmosphere, a hypothesis which is indeed required by the latitude and directional effects. Then, although each of these rays may *soften* as a result of its passage through the atmosphere, a suitably chosen energy distribution among the entering rays will insure that the measured radiation as a whole will harden with approach to sea level. The matter may be illustrated by considering the case of two distinct energies entering the atmosphere. Let the first, denoted by subscript unity, be the higher energy. For purposes of illustration we shall write, for some assigned direction,

$$n_1 = n_{10} e^{-\int \mu_1 dx}$$

This rather artificial looking expression is adopted because it corresponds to a coefficient of absorption, defined as $-(1/n_1)\,(dn_1/dx)$ which is equal to μ_1 and is variable with x, if μ_1 varies with x.

In a similar manner, we write

$$n_2 = n_{20}e - \int \mu_2 dx$$

The contribution of the two types of radiation is given by

$$n = n_1 + n_2 = n_{10}e - \int \mu_1 dx + n_{20}e - \int \mu_2 dx$$

The average coefficient of absorption of the combined radiation may be defined as $\mu = -(1/n)\ (dn/dx)$, so that

$$\mu = \frac{\mu_1 n_1 + \mu_2 n_2}{n_1 + n_2}$$

To illustrate the properties of this expression it will be sufficient to remark that if at x = 0, i. e., at entry to the atmosphere, n_1 is small compared to n_2, μ approximates μ_2. On the other hand at sufficiently large values of x, the quantity n_1 is large compared with n_2 on account of the required assumption that μ_2 shall be greater than μ_1. Hence at large values of x, the coefficient μ approximates μ_1. Thus, under the condition cited we have an illustration of the fact that, while the individual quantities μ_1 and μ_2 both increase with x, the measured μ decreases from μ_2 to μ_1, with increase of x.

It is not my purpose to attempt to fix too definitely, at this stage, the exact forms of the details of the various elements of the corpuscular theory here presented. It will suffice to say that, within the general spirit of the ideas outlined in the elementary form of the theory, it is possible to make modifications which will include all the experimental facts concerned with absorption in the atmosphere, and with the latitude and directional effects. By the farther hypothesis already cited, and to the effect that in the case of heavy atom elements, frequency of shower production and the like depend upon a higher power of the primary energy than the first, we are able to correlate with theory the experiments already cited in relation to such phenomena, together with a number of other experiments relating shower production to altitude, and to the characteristics of the primary rays as determined by their direction, or by their behavior in the matter of asymmetry.

In the foregoing discussion we have taken as the measured intensity, the intensity determined by the secondaries. We may regard each primary as accompanied by a number of secondaries equal to the product of the number emitted per

centimeter of path and the range of the secondaries. It is this latter quantity which, in the foregoing theory, determines the contribution of a simple primary to the measured intensity. If the primary itself ionizes, the contribution in question should be increased by unity. This does not disturb the essentials of the theory, however.

It is of interest to note that if q is the number of secondaries produced per centimeter of path by a primary, and if each secondary has an energy of 10^8 electron volts, the loss of energy per centimeter of path would be $q \times 10^8$. On the other hand, the loss of energy per centimeter of path at a place where the primary energy is E, is, according to the elementary theory, equal to μE, where μ is the absorption coefficient. Estimating all lengths in terms of centimeters of air compressed to the density of water, we have $\mu = 0.005$. Hence, $q \times 10^8 = 0.005\,E$. If E is of the order 10^{10} electron volts, $q = 0.5$. The range of 10^8 volt secondaries is of the order 20 cms in air compressed to the density of water. Hence the number of electrons accompanying each primary at the place where the primary energy is 10^{10} volts is of the order $20 \times 0.5 = 10$. The question of whether the primary is, or is not, added becomes therefore of small importance; although the importance is increased for smaller primary energies.

Any difficulty concerned with the participation of the primaries in direct ionization may be removed by a modification of the theory in which what we have already regarded as the primaries are really photons in their journey through the atmosphere. We must suppose that these photons receive their energy and their directional characteristics in their creation from the real charged particle primaries by impact of the latter with the atoms of air in the higher regions of the atmosphere. If then we impute to the photons the same characteristics of shower production, energy loss, etc., as we have imputed to the primaries in the foregoing discussion, the whole theory already given follows again in all its essential details. As the photons lose energy their frequencies of course change.

Possible Effects of Non-Ionizing Primaries:—The question of whether the high-energy primaries do, or do not, ionize is one which has interesting significance in another connection. Many years ago I was lead to study it in connection with the replenishment of the earth's charge. Through the action of

the conductivity of the atmosphere, the earth is sending off its charge into space at such a rate that 90 per cent of the charge would disappear in 10 minutes, if there were no means of replenishing the loss. A whole class of theories to account for the replenishment invoke, in some form or other, the principle of an influx of high-energy electrons into the earth. In order to account for the continual replenishment it is necessary to assume that 1,500 electrons enter each square centimeter of the earth's surface per second. If these electrons ionized air at the normal rate characteristic of reasonably high-energy electrons, they would produce 60,000 ions per cc. per second, whereas in practice we find less than 10 ions per cc. per second. For this reason I sought a theoretical mechanism by which it might be possible to conclude that a charged particle of sufficiently high energy would fail to ionize. In terms of the classical theories of electrodynamics it was found possible, satisfactorily, to realize such a theoretical possibility. With the advent of the wave mechanics I sought some means by which such a situation could be evolved out of that form of theory also. It was found possible to introduce in a natural way an extension of the wave mechanical principles to permit of such a possibility, and recently this extension has been put out and published in detailed form. At my request Dr. Bramley has applied the modified wave mechanical theory to the problem of ionization so as to work out the preliminary details of the mathematical mechanism by which the ionization for high energies becomes suppressed.

More recently the possibility that very high energy particles might not ionize received a renewed interest from the fact that cloud chamber measurements apparently failed to reveal as many high-energy electrons as would be demanded by the magnetic effects, a fact which could be understood if the high-energy electrons failed to ionize. A further field of interest in the matter concerns recent experiments by J. Clay on the intensity of cosmic radiation at various depths below the surface of water. Fig. 3 represents Clay's results on measurements of the ionization produced in a closed vessel at various depths. The ordinates represent the ratio of the ionization to the ionization at sea level. The significant thing about these observations is the fact that with increasing depth, the ionization diminishes, but at 100 meters of water, the curve starts to flatten out and actually shows a rise at 250 meters,

falling finally to zero at about 270 meters. It is possible to understand this state of affairs if we invoke the idea that the primary agency is a charged particle which does not ionize directly, but only through the intermediary of secondaries, but which, as it loses its energy, comes finally to an energy at which it commences to ionize directly. In this range of energy, it has a short period of renewed activity, represented by the hump at 250 meters in Fig. 3; but this activity represents as it were the dying gasp of the ray; for, at this stage its energy has reached a value at which its subsequent path in water is limited to twenty or thirty meters, after which its active life is spent. The complete story of the matter is a little more complicated than is here implied[8] but the details serve to enhance more than to detract from the reasonableness of the explanation.

Origin of Charged Particle Energy

The origin of charged particles of energies comparable with 10^{10} volts presents, of course, an interesting field for speculation. If the particles come from the stars, it is reasonably certain that positives and negatives must be emitted in equal numbers; for, if not, a star would soon become charged to an enormous potential which would prevent further departure. Thus, if the sun emitted from its surface no more electrons per square centimeter per second than fall per square centimeter per second on the surface of the earth as electron cosmic rays, it would charge at the rate of about 3×10^{10} volts per year. Since both signs must be emitted equally in the steady state, it is obvious that neither sign of charge can receive its energy from a potential field originating in the emitting body; and symmetrical from all parts of that body; for a field which would promote the departure of one sign would prevent the departure of the other.

A whole galaxy of stars with but small charge on each could, in the aggregate, secure for the galaxy a potential of large amount.[9] Consider a galaxy of radius R, containing N stars, each of radius a, and charged to a potential V in relation to a point sensibly infinitely distant from itself but yet falling

[8] W. F. G. Swann, The Significance of J. Clay's Ionization Depth Data in Relation to the Nature of the Primary Cosmic Radiation, Phy. Rev. 46, 432 (1934).

[9] W. F. G. Swann, "Methods of Acquirement of Cosmic Ray Energies," Phys. Rev. 42, 914 (1932); also "Cosmic Rays," The Military Engineer, 26, No. 146, 116–120, March-April, 1934.

within the galaxy. It can readily be shown that the potential at the surface of the galaxy is $W = V_a N/R$. If n is the number of stars per unit volume, this amounts to $4\pi R^2 V_a n/3$. This increases rapidly with R for fixed values of V, a, and n, so that, for sufficiently large values of R, W may be made large compared with V and we may secure a high potential difference between the body of the galaxy and intergalactic space by the assumption of a relatively small value of V. Unfortunately, when applied to the actual condition in the known galaxies, the possibilities of size are not sufficiently great to enable us to secure values of W even as great as V.

Apart from this, however, in such a charged galactic system, charged particles could dive through the galaxy, but particles of both signs could not enter. Such a situation, however, would lead us into difficulties of another kind, for, as I have shown elsewhere[10] if we had in the space between the stars a density of particles moving with the velocity of light and such as to correspond to a cosmic ray intensity equal to that observable upon the earth, they would, if of one sign, produce a space charge such as to give rise to differences of potential of the order of 10^{18} volts between points in space separated by no more than one light year. At first sight one might think that this difficulty could be alleviated by the existence of a sort of space charge of low energy particles, of sign opposite to those of the high energy particles. However, so long as the resultant field is of the right kind to draw into the galaxy particles of one sign and produce high energy in them, it could not permit the entry of particles of the opposite sign unless they themselves had high energy before entering.

A possibility exists for the acquirement of high energies by charged particles without the invocation of large potential differences.[11] A change in magnetic field produces an electromotive force in any circuit through which the flux is changing. Now we know that sunspots are associated with magnetic fields and, therefore, it is easy to believe that such spots would exist on the stars. The magnetic field of a sunspot can grow to about 2,000 gauss in about 10 days. Without invoking the stellar spots themselves as origin of cosmic ray energies, I wish

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[10]W. F. G. Swann, "Space Density of Cosmic Ray Particles," Phys. Rev. 44, 124, (1933).

[11]W. F. G. Swann, "A Mechanism of Acquirement of Cosmic-Ray Energies by Electrons," Phys. Rev. 43, 217 (1933).

merely to use them as evidence of the existence of changing magnetic fields upon these stellar bodies. The practical fact then is that if, over the region of a star, we have an area whose diameter is comparable with fifty times the diameter of the earth, and in which a magnetic field is growing at a rate comparable with that at which it grows in a sunspot, then through the processes of electromagnetic induction, an electron would acquire an energy of 10^{10} volts in one second, and before the field has grown to more than one-thousandth of a gauss.

I may cite another possibility of a more speculative nature, but possessing nevertheless certain advantages.[12]. Many years ago, in order to provide an explanation of the earth's charge, of its magnetic field and several other matters, I proposed a modified scheme of electrodynamics. One of the consequences of this scheme was the prediction of a slow death of the positive charge in the case of a rotating body so that the surplus negative gradually accumulated until it built up a field in the atmosphere which insured that it passed away from the earth's surface at a constant rate such as would maintain equilibrium. If now, on the basis of this hypothesis we continue to trace the passage of electricity off into space, we see a growing volume distribution of electricity thinning out in density as we go outwards but continually increasing in total amount. This growing volume of electricity produces a difference of potential between the sphere and a point infinitely distant from it. If we allow the process to go on for an infinite time we find that the potential difference amounts to infinity, but the rate at which it mounts gets so slow as time goes on, that even astronomical times are not sufficient to result in more than differences of potential which, though large, are of an order of magnitude significant in cosmic ray phenomena. Thus if we should consider a star as large as the sun, with a surface density of current equal to that for the earth, we should find that in seventy years the potential difference between the star and infinity would have grown to about 6×10^9 volts. In order for it to grow to six times this amount 70 million years would be necessary, so that, as I have remarked, even the invocation of astronomical time would not lead to potentials which were out of the realm of reason. As a matter of fact, the actual situation arising out of the physical mechanism which this example is designed to

[12]W. F. G. Swann, "Cosmical Electrical Fields," Phys. Rev. 45, 295, (1934).

illustrate becomes complicated by various considerations involving the distances of the galactic systems from each other, the places of origin of cosmic rays, and so forth. All that I wish to emphasize is the possibilities inherent in a situation of this kind for the realization of potential differences of the order of magnitude comparable with those encountered in cosmic ray phenomena and such extrapolations into the regions of even higher energy as reason would permit.

Perhaps one of the easiest ways of accounting for the existence of high-energy particles is through the actions of phenomena analogous to thunderstorms in the stars. A thunderstorm is simply the result of the operation of a large electrical machine; and the fundamental principle of its operation is one in which positive and negative electrons are separated in amounts and through distances such as result in large difference of potential by using the tremendous forces of gravity acting on matter for the most part neutral. Even in the thunderstorm on earth, potential differences of the order of 10^9 volts can arise. An electron coming under the influence of the corresponding fields would become accelerated. Under suitable conditions, as C. T. R. Wilson has shown, it is possible for an electron to acquire energy in this way faster than it loses it to the surrounding gas. Moreover, the higher the energy of the electron, the less does it fritter away its energy. The electron is like a man who spends less and less as he acquires more and more wealth. Once the electron has surmounted its initial difficulties in getting started it can acquire energy equal to that determined by the potential differences available. Now, when we think of the enormous activities taking place in stars—particularly in novae, it would not be surprising if phenomena analogous to thunderstorms, or at any rate the essentials of an electrical machine, could exist on them such as would give rise to potential differences of the order of 10^{10} volts, or more. One need not make the mistake of thinking that because a star is neutral as a whole there cannot exist on it a point which has a finite electrical potential in relation to infinity. For in a system composed, for example, of two adjacent spheres equally charged, one positively and the other negatively, there is between the positive charge and infinity a difference of potential comparable in fact with M/r^2, where M is the moment of the combined spheres, and r is half the distance between them.

In case we look to the stars as the source of cosmic radiation it is natural to suppose that our sun is not in a condition to be a contributor; for, if it were, it would be natural to suppose that it was the main contributor in view of its proximity, just as it is the main contributor of light. Finally, however, one must make a remark to the effect that even if the sun did contribute an appreciable amount of the cosmic radiation in the form of charged particles, it would not be so easy to detect the fact as might be supposed; for, in view of the complicated influence of the earth's magnetic field, the contributions from various parts of space would have very little relation to any special increase of intensity in the geometrical direction of the sun itself.

Orientation in Science

The development and increasing popularity of orientation courses in science for college freshmen have created a need for textbooks to accompany such courses. This volume is the outcome of such a need. It is an attempt to give the student a rational and synoptic outlook upon man and the universe. The evaluation of this particular effort presents the reviewer with a difficult task. The book contains much meat, but it is largely hidden in a mass of generalities and platitudes. At times it seems doubtful whether the student will be able to take away any specific facts at all; then in places the book is clearly and succinctly written, only to bog down again in a morass of meandering and essentially meaningless phraseology. The physical sciences are treated in much better fashion than the biological sciences. A particularly good point is the binding and cohesive development of evolution (cosmic, geological and organic) as a great unifying technique. Conversely, a particularly bad point is the constant untiring use of italics and quotation marks. All desirable emphasis is lost by the over-use of these potentially valuable forms of accent. Opening the volume at random, a typical page contains 65 words in italics and 17 words in quotation marks. This is a positive detraction. The book may appeal to the philosophically-minded student, but is not conducive to clear thinking or concrete orientation on the part of the many. In the opinion of this reviewer, the book defeats its own purpose.—L. H. S.

The Backgrounds and Foundations of Modern Science, by Richard E. Lee. xxv+536 pp. Baltimore, the Williams and Wilkins Co. 1935.

The Origin of the Solar System

For those who have become "universe-conscious" as a result of the writings of Jeans, Eddington and the rest, this well-written volume will provide the next step in adventures in cosmic thinking. It is a clear, stimulating account of the properties and workings of the sun, the planets, the satellites, the asteroids, the comets and the meteors. In technical difficulty it is a good step above the strictly popular volumes, but it is so clearly and directly written that the step is an easy one, and well worth the taking. The book represents the Page-Barbour Foundation Lectures given at the University of Virginia in 1934. The first two sections on the dynamical and physico-chemical properties of the solar system lead up to the important and thought-provoking third section, which discusses in detail the postulated theories of the origin of the system. Recent new and little-known data are presented, and the author's own hypothesis of origin is elaborated. After an hour or two of letting one's fancy roam afar in space and time, one ceases to worry about the expected letter that is three days overdue.—L. H. S.

The Solar System and its Origin, by Henry Norris Russell. 141 pp. New York, the Macmillan Co. 1935.

ENERGIES AND PRODUCTS INVOLVED IN NUCLEAR DISINTEGRATION AND SYNTHESIS

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INTRODUCTION

There seems to be running through the multitude of experiments that have been performed in the last year or so on nuclear disintegration, a strong demand for certain fundamental nuclear building blocks. These building blocks with their properties and their current scientific standing are listed in Table I (1).

TABLE I
Building Blocks

	Mass	Charge	Symbol	Reputability
Electron	Very small	neg.	e	Long standing
Neutrino	Very small	zero	n'	Questionable
Positron	Very small	pos.	e^+	Recently established
Negatron	Large	neg.	p	Questionable
Neutron	Large	zero	n	Recently established
Proton	Large	pos.	p	Long standing

It is noticed that there are two major groups; a group of three with small masses and a group of three with large masses. The relative size of the masses in these two groups is about 1/1850 to 1.

A few years ago when only the two particles, the electron and the proton, were known, many attempts were made to build consistent arrays of the known nuclei out of these two constituents. However, when the reality of the neutron was established (2) and when sufficient experimental data on how nuclei disintegrate were accumulated, it became obvious that the previous concepts on nuclear building were inadequate and erroneous.

STABLE NUCLEI

Since only protons and neutrons (or combinations of these; for example, an alpha particle which consists, let us say, of two protons and two neutrons) are found ejected when a nucleus is made to disintegrate, it is natural to expect the nuclei of the various elements to be made up of a logical sequence of protons and neutrons (3). Table II shows a possible arrangement.

TABLE II

ATOMIC MASSES

	Composition	Bethe	Oliphant	Aston et al.
$_0n^1$	n	1.00850 (50)*	1.0083 (3)	1.0089
$_1H^1$	p	1.00807 (07)	1.0081 (1)	*1.0081*
$_1H^2$	n p	2.01423 (15)	2.0142 (2)	*2.0148*
$_1H^3$	n p n	3.01610 (33)	3.0161 (3)	3.0151
$_2He^4$	α	4.00336 (23)	4.0034 (4)	*4.0041*
$_2He^5$	α n	.....	5.010 ...	5.0060
$_3Li^6$	α n p	6.01614 (50)	6.0163 (6)	6.0175
$_3Li^7$	α n p n	7.01694 (48)	7.0170 (7)	7.0176
$_4Be^8$	2α	.....	8.007 ...	.....
$_4Be^9$	2α n	9.0135 (7)	9.0138 (5)	9.0164
$_5B^{10}$	2α n p	10.0146 (10)	10.0143 (3)	10.0135
$_5B^{11}$	2α n p n	11.0111 (11)	11.0110 ...	11.0121
$_6C^{12}$	3α	12.0037 (7)	12.0027 (3)	*12.0048*
$_6C^{13}$	3α n	13.0069 (7)	.....	13.0051
$_7N^{14}$	3α n p	14.0076 (4)	.....	14.0042
$_7N^{15}$	3α n p n	15.0053 (5)	.....	15.0032
$_8O^{16}$	4α	16.0000 (0)	16.0000 (0)	16.0000
$_8O^{17}$	4α n	17.0040 (2)	.....	17.0024
$_8O^{18}$	4α n n	.....	.....	18.0065
$_9F^{19}$	4α n n p	.....	.....	18.9931
$_2He^3$	p n p	3.01699 (46)	3.0172 (3)	3.0164

*The numbers in parentheses indicate the probable error; for example, 1.00850 + .00050.

First, there is the neutron and the proton separately. Next, there is the combination of neutron and proton, called the deuteron or nucleus of the heavy hydrogen atom of which heavy water is made. By adding a neutron to this nucleus there is obtained a still heavier nucleus of hydrogen. The addition of a proton to this nucleus then gives the alpha particle or the nucleus of the helium atom. It is obvious that the

nuclei following from here on may be arrived at by merely adding alternately a neutron and proton—until oxygen, atomic number 8, atomic weight 16, is reached. Then the scheme is to add neutron, neutron, proton, proton.

As may be seen in Table III this scheme continues to argon. Beyond argon a more complicated scheme involving the negatron seems to work more satisfactorily (4). In Table II are listed also the nuclear masses as given by three different workers. The masses given by the first two are based on nuclear disintegration data, the last based on mass spectrograph data (5). It is unfortunate that there is such a wide spread in the data available and that no definite values as yet can therefore be decided upon.

TABLE III

STABLE NUCLEI

Nucleus	Composition	Mass	Abundance
$_1H^1$	p	1.00807	99.99
$_1H^2$	n p	2.01423	.025
$_1H^3$	n p n	3.01610	10^{-6}
$_2He^4$	α	4.00336	100
$_2He^5$	α n	5.010	.....
$_3Li^6$	α n p	6.01614	8.3
$_3Li^7$	α n p n	7.01694	91.7
$_4Be^8$	2α	8.007	.05
$_4Be^9$	2α n	9.0135	99.99
$_5B^{10}$	2α n p	10.0146	20.
$_5B^{11}$	2α n p n	11.0111	80
$_6C^{12}$	3α	12.0037	99.75
$_6C^{13}$	3α n	13.0069	.25
$_7N^{14}$	3α n p	14.0076	99.86
$_7N^{15}$	3α n p n	15.0053	.14
$_8O^{16}$	4α	16.0000	99.81
$_8O^{17}$	4α n	17.0040	.03
$_8O^{18}$	4α n n	18.0065	.16
$_9F^{19}$	4α n n p	19.0031	100
$_{10}Ne^{20}$	5α	19.99671	90.4
$_{10}Ne^{21}$	5α n	.....	0.6
$_{10}Ne^{22}$	5α n n	21.99473	9.0
$_{11}Na^{23}$	5α n n p	.....	100
$_{12}Mg^{24}$	6α	.....	77.4
$_{12}Mg^{25}$	6α n	.....	11.5
$_{12}Mg^{26}$	6α n n	.....	11.1
$_{13}Al^{27}$	6α n n p	.....	100
$_{14}Si^{28}$	7α	27.9818	94

TABLE III—(Continued)

Nucleus	Composition	Mass	Abundance
$_{14}Si^{29}$	7*a* n	.....	4
$_{14}Si^{30}$	7*a* n n	.....	2
$_{15}P^{31}$	7*a* n n p	30.9825	100
$_{16}S^{32}$	8*a*	.....	96
$_{16}S^{33}$	8*a* n	.....	1
$_{16}S^{34}$	8*a* n n	.....	3
$_{17}Cl^{35}$	8*a* n n p	34.893	76
$_{18}A^{36}$	9*a*	35.976	0.6
$_{18}A^{37}$	9*a* n	.....	.....
$_{18}A^{38}$	9*a* n n	.....	.....
$_{19}K^{39}$	9*a* n n p	.....	5.4
$_{18}A^{36}$	9*a*	35.976	0.6
$_{17}Cl^{37}$	9*a* *p*	36.980	24
$_{18}A^{38}$	9*a* *p* p	.....	.01
$_{18}A^{39}$	9*a* *p* p n	.....	.....
$_{18}A^{40}$	9*a* *p* p n n	39.971	99.4
$_{20}Ca^{40}$	10*a*	.....	97
$_{19}K^{41}$	10*a* *p*	.....	94.6
$_{20}Ca^{42}$	10*a* *p* p	.....	.8
$_{20}Ca^{43}$	10*a* *p* p n	.....	.2
$_{20}Ca^{44}$	10*a* *p* p n n	.....	2.3
$_{22}Ti^{44}$	11*a*	.....	.....
$_{21}Sc^{45}$	11*a* *p*	.....	100
$_{22}Ti^{46}$	11*a* *p* p	.....	.01
$_{22}Ti^{47}$	11*a* *p* p n	.....	.01
$_{22}Ti^{48}$	11*a* *p* p n n	.....	99
$_{22}Ti^{49}$	11*a* *p* p n n n	.....	.01
$_{22}Ti^{50}$	11*a* *p* p n n n n	.....	.01
$_{24}Cr^{50}$	12*a* 2n	.....	4.9
$_{23}V^{51}$	12*a* 2n *p*	.....	100
$_{24}Cr^{52}$	12*a* 2n *p* p	.....	81.6
$_{24}Cr^{53}$	12*a* 2n *p* p n	.....	10.4
$_{24}Cr^{54}$	12*a* 2n *p* p n n	.....	3.1
$_{26}Fe^{54}$	13*a* 2n	.....	95
$_{25}Mn^{55}$	13*a* 2n *p*	.....	100
$_{26}Fe^{56}$	13*a* 2n *p* p	.....	5
$_{26}Fe^{57}$	13*a* 2n *p* p n	.....	.....
$_{26}Fe^{58}$	13*a* 2n *p* p n n	.....	.....
$_{28}Ni^{58}$	14*a* 2n	57.942	66
$_{27}Co^{59}$	14*a* 2n *p*	.....	100
$_{28}Ni^{60}$	14*a* 2n *p* p	.....	34
$_{28}Ni^{61}$	14*a* 2n *p* p n	.....	.01
$_{28}Ni^{62}$	14*a* 2n *p* p n n	.....	.01
$_{29}Cu^{63}$	14*a* 2n *p* p n n p	.....	68
$_{30}Zn^{64}$	15*a* 4n	63.937	50.4
$_{29}Cu^{65}$	15*a* 4n *p*	.....	32

TABLE III—(Continued)

Nucleus	Composition	Mass	Abundance
$_{30}Zn^{66}$	15*a* 4n *p* p	.....	27.2
$_{30}Zn^{67}$	15*a* 4n *p* p n	.....	4.2
$_{30}Zn^{68}$	15*a* 4n *p* p n n	.....	17.4
$_{31}Ga^{69}$	15*a* 4n *p* p n n p	.....	60
$_{30}Zn^{70}$	15*a* 4n *p* p n n p *p*	.....	0.4
$_{32}Ge^{70}$	16*a* 6n	.....	21.2
$_{31}Ga^{71}$	16*a* 6n *p*	.....	40
$_{32}Ge^{72}$	16*a* 6n *p* p	.....	27.3
$_{32}Ge^{73}$	16*a* 6n *p* p n	.....	7.9
$_{32}Ge^{74}$	16*a* 6n *p* p n n	.....	37.1
$_{33}As^{75}$	16*a* 6n *p* p n n p	74.934	100
$_{32}Ge^{76}$	16*a* 6n *p* p n n p *p*	.....	6.5

NEUTRONS

By glancing over Table III several points of interest are noticed; for example, beryllium, atomic number 4, atomic weight 9, is the only nucleus with any appreciable abundance that has attached to its alpha-particle kernel only one single extra neutron. As might be expected this extra neutron (under violent bombardment with alpha rays from polonium) would easily be shaken loose and neutron emission observed. In fact this is the very way neutrons were first discovered by Chadwick in 1932. Consequently, were it not for the existence of this particular isotope of beryllium which copiously emits neutrons, the field of nuclear physics would undoubtedly be less advanced and less fruitful than it is today and nuclear physicists would be deprived of one of their most powerful tools for prying into the secrets of the nucleus.

Table IV has been prepared in order to show clearly what is meant by the terms *isotopes*, *isobars*, and *isomers*.

TABLE IV

Isotopes, Isobars, Isomers

	Weight of Nucleus	Chemical Properties of Atom	Structure of Nucleus	Examples
Isotopes	Different...	Same.....	Different...	$_1H^1$, $_1H^2$, $_1H^3$
Isobars	Same.....	Different...	Different...	$_1H^3$, $_2He^3$
Isomers	Same.....	Same.....	Different...	$_{91}UX_2$,^{234} $_{91}UZ^{234}$

Since the advent of neutrons through the bombardment of beryllium by alpha rays, many attempts have been made to discover or develop other methods that would give strong neutron sources. The three most successful methods are deuteron bombardment of beryllium, deuteron bombardment of the heavier lithium isotope, and deuteron bombardment of deuterons. With four strong neutron sources available, much progress in nuclear transformations has been made by using the neutrons obtained from nuclear disintegration to bombard and thereby disintegrate other nuclei.

SYNTHESIZED RADIOACTIVE NUCLEI

When a nucleus is disintegrated, or rather transmuted, into some other nucleus, it frequently occurs that the nucleus which is formed is of a new species and has never been observed before. In order to show how fruitful this particular phase of the general nuclear problem is, there is collected in Table V a list of nuclei which were not known to either chemists or physicists before February, 1934. F. Joliot and I. Curie (6) announced then that alpha-ray bombardment of boron produces a product which is radioactive. This product is nitrogen, atomic number 7, atomic weight 13 (see eleventh row), composed of three alpha particles and one proton, has a half life of 11 minutes, emits positrons with energies up to 1.5 million volts, and as may be seen in the last column of the table, can be produced also by proton bombardment of carbon or by deuteron bombardment of carbon.

TABLE V

SYNTHESIZED RADIOACTIVE NUCLEI

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_2He^3$	p n p	.....	.....	.....	p Li^6; d (H^2, B^9)
$_2He^6$	α n n	.....	.....	.....	.....
$_3Li^5$	α p	.....	.....	.....	.....
$_3Li^8$	α n n p n	0.5 s	9. mV max	—	d Li^7
$_4Be^7$	α p n p	.....	.....	.....	.....
$_4Be^{10}$	2α n n	.....	.3 mV av	—	d Be^9; α Li^7
$_5B^9$	2α p	1. m	.5 mV av	+	α Li^6
$_5B^{12}$	2α n n p n	.02 s	11. mV max	—	d B^{11}
$_6C^{11}$	2α p n p	20. m	1.3 mV max	+	d B^{10}
$_6C^{14}$	3α n n	.....	.....	.....	.....
$_7N^{13}$	3α p	11. m	1.5 mV max	+	p C^{12}; d C^{12}; α B^{10}

TABLE V—(Continued)

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_{7}N^{16}$	3α n n p n	9. s	.....	—	n F^{19}
$_{8}O^{15}$	3α p n p	126. s	1.2 mV max	+	d N^{14}
$_{8}O^{19}$	4α n n n	40 s	.....	—	n F^{19}
$_{9}F^{17}$	4α p	1.16 s	.....	+	α N^{14}
$_{9}F^{18}$	4α n p	.....	.....	+	.....
$_{9}F^{20}$	4α n n p n	12. s	4.5 mV max	—	n Na^{23}; d F^{19}
$_{10}Ne^{19}$	4α p n p	.....	.....	+	.....
$_{10}Ne^{23}$	5α n n n	40. s	.....	—	n (Na^{23}, Mg^{26})
$_{11}Na^{22}$	5α n p	.....	.4 mV av	+	α F^{19}
$_{11}Na^{24}$	5α n n p n	15. h	1.0 mV av	—	n (Na^{23}, Mg^{24}, Al^{27}) d Na^{23}
$_{12}Mg^{23}$	5α p n p	.....	.....	+	.....
$_{12}Mg^{27}$	6α n n n	10. m	.6 mV av	—	n (Mg^{26}, Al^{27})
$_{13}Al^{26}$	6α n p	.....	.....	+	.....
$_{13}Al^{28}$	6α n n p n	2.3 m	1.3 mV av	—	n (Al^{27}, Si^{28}, P^{31}); d Al^{27}; α Mg^{25}
$_{14}Si^{27}$	6α p n p	14.5 m	.....	+	α Mg^{24}
$_{14}Si^{31}$	7α n n n	2.4 h	1.25 mV av	—	n (Si^{30}, P^{31})
$_{15}P^{30}$	7α n p	3.25m	3. mV max	+	α Al^{27}
$_{15}P^{32}$	7α n n p n	14. d	.8 mV av	—	n (S^{32}, Cl^{35})
$_{16}S^{31}$	7α p n p	.....	.....	+	.....
$_{16}S^{35}$	8α n n n	.....	.....	—	.....
$_{17}Cl^{34}$	8α n p	.....	.....	+	.....
$_{17}Cl^{36}$	8α n n p n	50. m	2. mV max	—	n Cl^{35}
$_{17}Cl^{38}$	9α p n	.....	.....	—	n Cl^{37}
$_{18}A^{35}$	8α p n p	.....	.....	+	.....
$_{18}A^{39}$	9α n n n	.....	.....	—	.....
$_{19}K^{38}$	9α n p	.....	.....	+	.....
$_{19}K^{42}$	10α p n	16. h	1.6 mV av	—	n (K^{41}, Sc^{45}, Ca^{42})
$_{20}Ca^{41}$	10α n	4. h	.....	—	n Ca^{40}
$_{20}Ca^{45}$	10α p p n n n	3. m	.....	—	n Ti^{48}
$_{21}Sc^{46}$	11α p n	.....	.....	.....	n Sc^{45}
$_{23}V^{52}$	.....	3.75m	1.4 mV av	—	n (V^{51}, Cr^{52}, Mn^{55})
$_{25}Mn^{56}$	.....	2.5 h	1.2 mV av	—	n (Mn^{55}, Fe^{56}, Co^{59})
$_{29}Cu^{64}$	.....	5. m	.....	—	n (Cu^{63}, Zn^{64})
$_{29}Cu^{66}$	.....	10. h	.....	—	n (Cu^{65}, Zn^{66})
$_{31}Ga^{70}$	.....	20. m	1.4 mV av	—	n Ga^{69}
$_{31}Ga^{72}$	.....	23. h	.....	—	n Ga^{71}
$_{32}Ge^{75}$	.....	30. m	.....	—	n Ga^{74}
$_{33}As^{76}$	.....	26. h	1.3 mV av	—	n As^{75}
$_{34}Se^{81}$	.....	35. m	.....	—	n Se^{80}
$_{35}Br^{80}$	.....	30. m	2.1 mV max	—	n Br^{79}
$_{35}Br^{82}$	.....	6. h	2.1 mV max	—	n Br^{81}
$_{40}Zr^{95}$	.....	4. h	1.1 mV av	—	n Zr^{94}
$_{42}Mo^{99}$	.....	30. m	.....	—	n Mo^{98}
$_{42}Mo^{101}$	.....	36. h	.....	—	n Mo^{100}

TABLE V—(Continued)

Nucleus	Composition	Life	Energy of e	+or—	Method of Production
$_{45}Rh$	.....	44. s	1.2 mV av	—	n Rh
$_{45}Rh$	.....	3.9 m	.....	—	n Rh
$_{47}Ag^{108}$	.....	22. s	.....	—	n Ag^{107}
$_{47}Ag^{110}$	.....	2.3 m	.7 mV av	—	n Ag^{109}
$_{49}In^{114}$	.....	54. m	.7 mV av	—	n In^{113}
$_{49}In^{116}$	.....	3. h	.....	—	n In^{115}
$_{51}Sb^{122}$	.....	2.5 d	.7 mV av	—	n Sb^{121}
$_{52}Te^{131}$	.....	45. m	.....	—	n Te^{130}
$_{53}I^{128}$	.....	30. m	2.1 mV max	—	n I^{127}
$_{55}Cs^{134}$	.....	1.5 h	.....	—	n Cs^{133}
$_{56}Ba^{139}$	.....	80. m	.....	—	n Ba^{138}
$_{58}Ca^{141}$	.....	5. m	.....	—	n Pr^{141}
$_{59}Pr^{142}$	.....	19. h	1. mV av	—	n Pr^{141}
$_{60}Nd^{147}$	.....	1. h	.....	—	n Nd^{146}
$_{62}Sm^{153}$	.....	40. m	.....	—	n Sm^{152}
$_{64}Gd^{159}$	.....	8. h	.....	—	n Gd^{158}
$_{72}Hf^{181}$	.....	2. mo	.....	—	n Hf^{180}
$_{74}W^{185}$	.....	1. d	.....	—	n W^{184}
$_{75}Re^{186}$	.....	20. h	1. mV av	—	n Re^{185}
$_{77}Ir$	.....	19. h	1. mV av	—	n Ir
$_{78}Pt$	.....	50. m	.....	—	n Pt
$_{79}Au$	.....	2.7 d	.4 mV av	—	n Au
$_{90}Th$	.....	1. m	.....	—	n Th^{232}
$_{90}Th$	.....	24. m	.....	—	n Th^{232}
$_{92}U$	.....	15. s	.....	—	n U^{238}
$_{92}U$	.....	40. s	.....	—	n U^{238}
?	.....	13. m	1.2 mV av	—	n U^{238}
?	.....	100. m	.6 mV av	—	n U^{238}

Helium, atomic number 2, atomic weight 3 (see first row), has not been observed to be radioactive, nevertheless it is listed in this table with the synthesized nuclei because it fits in with their scheme of nuclear composition. Every nucleus in this table does not fit in with the scheme for stable nuclei in Table III. However, there apparently is no great fundamental difference between stable nuclei and unstable nuclei since the half life of the synthesized nucleus hafnium is two months.

It is interesting to notice that the lighter synthesized nuclei can be obtained in several ways while the heavier synthesized nuclei must be obtained only with neutron bombardment (7). To make somewhat more clear the implication of the shorthand of the last column of Table V, there is written out in

Table VI the details for the various ways in which radioactive sodium, or rather radio-sodium, can and may be synthesized. Similar information in regard to radio-aluminum is given in Table VII. The upper group of reactions in each of these tables are those reactions that have been observed to work satisfactorily; the lower group are those that might work if the various nuclei involved existed or existed in sufficient abundance.

TABLE VI

RADIO-SODIUM

$$_0n^1 + {}_{11}Na^{23} \longrightarrow {}_{11}Na^{24}$$
$$_0n^1 + {}_{12}Mg^{24} \longrightarrow {}_{11}Na^{24} + {}_1p^1$$
$$_0n^1 + {}_{13}Al^{27} \longrightarrow {}_{11}Na^{24} + {}_2He^4$$
$$_1d^2 + {}_{11}Na^{23} \longrightarrow {}_{11}Na^{24} + {}_1p^1$$

$$_1d^2 + {}_{12}Mg^{26} \longrightarrow {}_{11}Na^{24} + {}_2He^4$$
$$_2\alpha^4 + {}_{10}Ne^{21} \longrightarrow {}_{11}Na^{24} + {}_1p^1$$
$$_2\alpha^4 + {}_9F^{21} \longrightarrow {}_{11}Na^{24} + {}_0n^1$$
$$_1d^2 + {}_{10}Ne^{23} \longrightarrow {}_{11}Na^{24} + {}_0n^1$$
$$_1p^1 + {}_{10}Ne^{24} \longrightarrow {}_{11}Na^{24} + {}_0n^1$$
$$_1p^1 + {}_{12}Mg^{27} \longrightarrow {}_{11}Na^{24} + {}_2\alpha^4$$

$$_{11}Na^{24} \xrightarrow[15h]{} {}_{12}Mg^{24} + -{}_1e^0$$

TABLE VII

RADIO-ALUMINUM

$$_0n^1 + {}_{13}Al^{27} \longrightarrow {}_{13}Al^{28}$$
$$_0n^1 + {}_{14}Si^{28} \longrightarrow {}_{13}Al^{28} + {}_1H^1$$
$$_0n^1 + {}_{15}P^{31} \longrightarrow {}_{13}Al^{28} + {}_2He^4$$
$$_1d^2 + {}_{13}Al^{27} \longrightarrow {}_{13}Al^{28} + {}_1H^1$$
$$_2\alpha^4 + {}_{12}Mg^{25} \longrightarrow {}_{13}Al^{28} + {}_1H^1$$

$$_1d^2 + {}_{14}Si^{30} \longrightarrow {}_{13}Al^{28} + {}_2He^4$$
$$_1d^2 + {}_{12}Mg^{27} \longrightarrow {}_{13}Al^{28} + {}_0n^1$$
$$_2\alpha^4 + {}_{11}Na^{25} \longrightarrow {}_{13}Al^{28} + {}_0n^1$$
$$_1p^1 + {}_{12}Mg^{28} \longrightarrow {}_{13}Al^{28} + {}_0n^1$$
$$_1p^1 + {}_{14}Si^{31} \longrightarrow {}_{13}Al^{28} + {}_2He^4$$

$$_{13}Al^{28} \xrightarrow[2.3m]{} {}_{14}Si^{28} + -{}_1e^0$$

If one is to prohibit electrons and positrons from being constituents in the building up of the nucleus, perhaps the necessity of accounting for the actual experimentally observed ejections of electrons and positrons from these radioactive nuclei would consequently produce some embarrassment. However, one is able to account satisfactorily for the emission of light from an atom without the necessity of saying that atoms are composed, in part at least, of light. Likewise, when a nucleus changes from one energy state to another of lower energy, the energy difference may be carried from the nucleus

in the form of a gamma ray or if there is sufficient excess energy in the form of an electron (or positron) which is created out of this energy in accord with the Einstein relativistic relation that energy equals mass multiplied by the square of the velocity of light.

SLOWED NEUTRONS

It is the common opinion that the faster the impinging bombarding particle is made to go, the more likely it is upon

TABLE VIII

SLOW-NEUTRON EFFECTIVENESS

Element Bombarded	Effectiveness of Slow Neutrons Over That of Fast
Vanadium	40
Silver	30
Manganese	23
Rhodium	15
Tungsten	15
Copper	15
Indium	12
Bromine	10

TABLE IX

ABSORBERS OF SLOW NEUTRONS (7)

Element	Thickness Required to Decrease Intensity of a Beam of Slow Neutrons to Half
Cadmium	.015 mm., .13 mm. (14)
Boron	.022 mm.
Yttrium	.040 mm.
Lithium	.094 mm.

collision for a disintegration to take place. This idea has recently been shown to be grossly wrong in a large number of the reactions where neutron bombardment is concerned. In Table VIII there are listed some of the elements which show a marked increase of effectiveness of slow neutrons compared to the effectiveness of fast neutrons in the production of radioactive nuclei (8). Other elements which do not yield radioactive nuclei when bombarded with neutrons evidence their reactional tendencies by strongly absorbing a beam of slow neutrons.

For example, the substances in Table IX are considered opaque to slow neutrons. However, some other substances such as aluminum, tin, zinc, and iron are comparatively transparent to slow neutrons. Almost all substances are easily penetrated by fast neutrons.

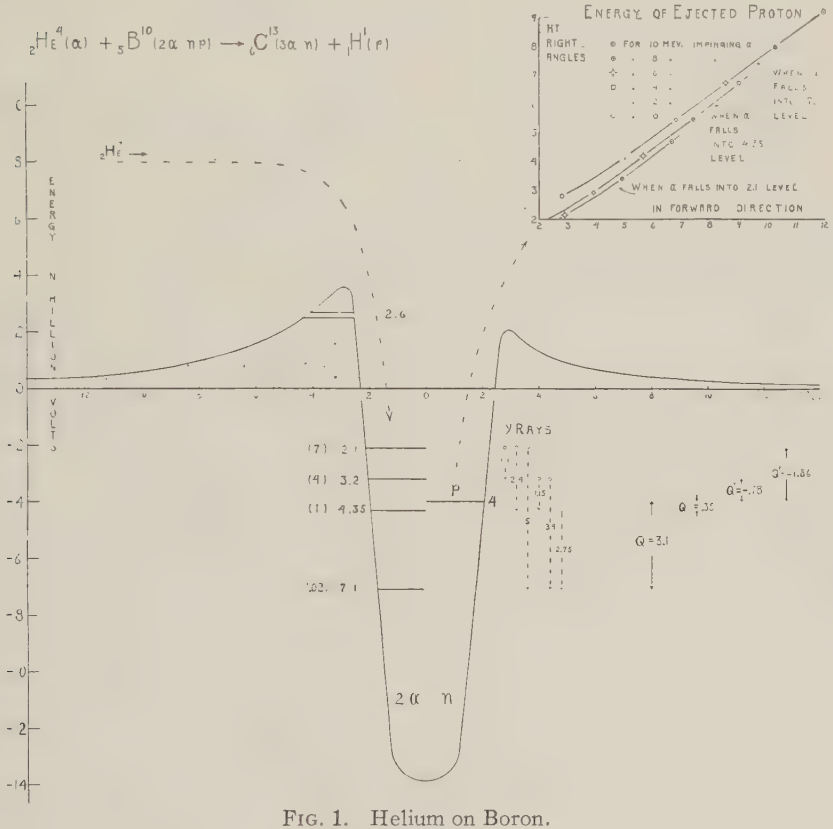

FIG. 1. Helium on Boron.

TRANSMUTATION DIAGRAMS

Since it is quite evident by now that there is a large quantity of information available concerning nuclear transmutations in general and concerning the behavior of any one nucleus in a transmutation, a collection, therefore, of a portion of this information condensed as much as possible into a single diagram or schematic picture would possibly be desirable.

With this purpose in mind consider Fig. 1 for the transmutation of boron into carbon and hydrogen (9). Along the

vertical axis is plotted energy in million volts and along the horizontal axis is plotted nuclear distance in 10^{-13} cm. The left half of the diagram represents the potential energy curve

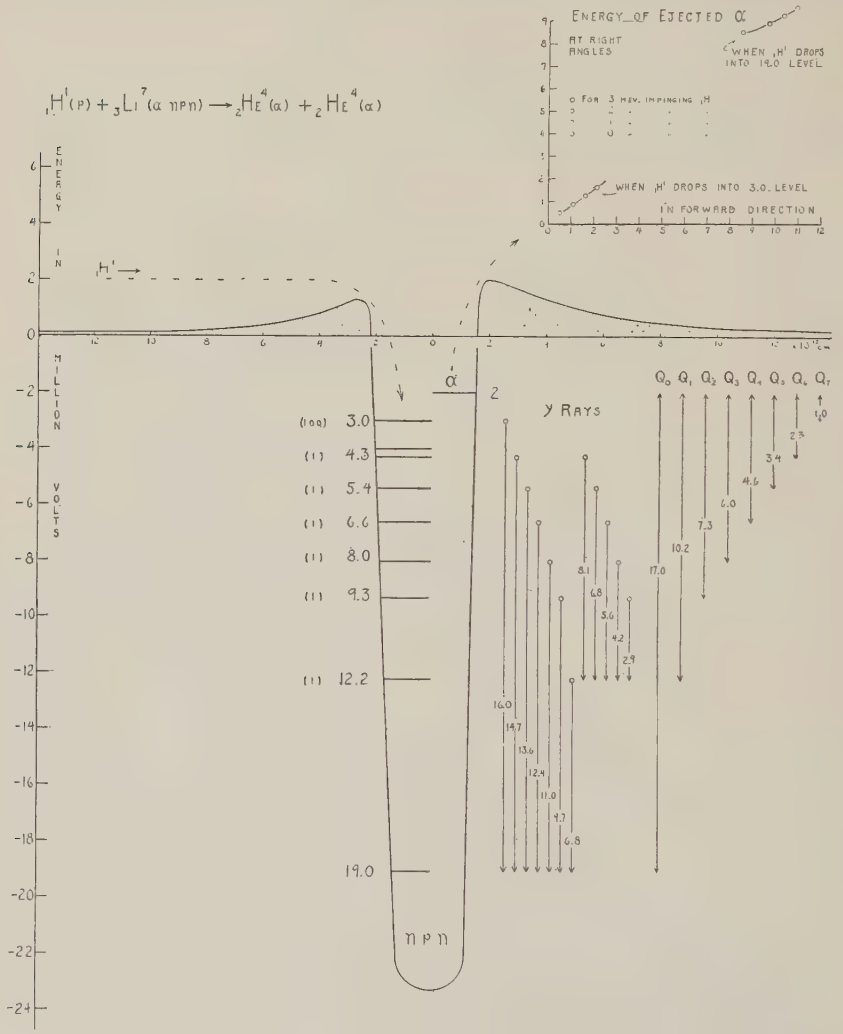

FIG. 2. Protons on Lithium.

or potential barrier of an alpha particle in the presence of a boron nucleus. This is the situation before the transmutation. The right-hand curve represents the potential energy curve or potential barrier of a proton in the presence of a carbon

nucleus. This is the situation after transmutation. The diagram is then to be read as follows: The alpha particle approaches the boron nucleus and is repulsed by the strong electric fields. If the alpha particle has enough energy to get over the barrier, which here is about 3.6 million volts, it then falls into the interior of the nucleus. There are four levels (2.1, 3.2, 4.35, and 7.1 million volt) on which the alpha particle may choose to stop. If the alpha particle drops to the lowest

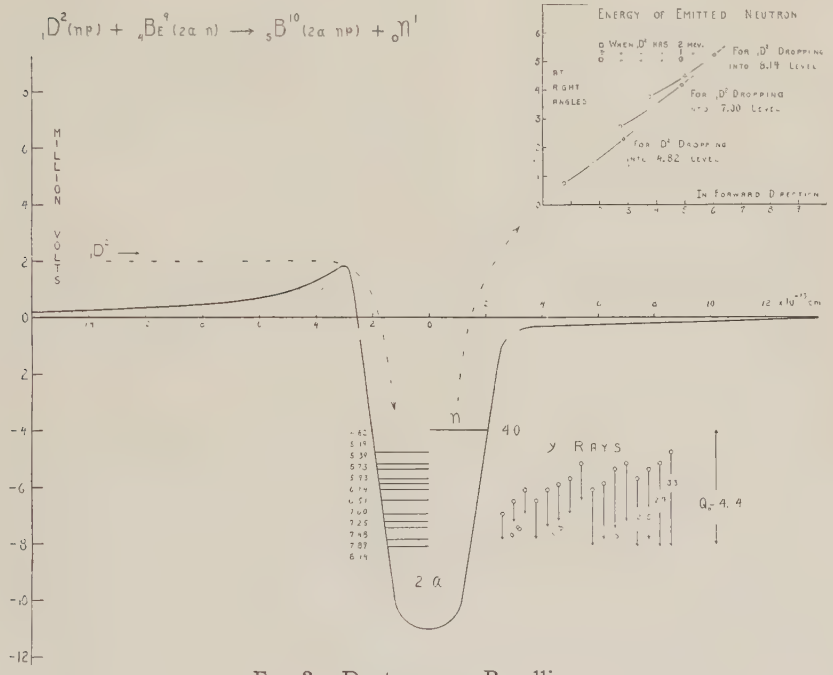

Fig. 3. Deuterons on Beryllium.

level, the greatest amount of energy is available to eject the proton from its four-million-volt level.

The proton may be ejected in the same direction as the impinging alpha particle or at right angles to this direction. Due to the conservation of momentum the proton will receive a little more energy if it comes off in the forward direction. Taking into consideration the momentum of the impinging alpha particle, the recoil of the residual carbon nucleus and the true transmutation energy Q, calculations were made for the energies of the protons in both the forward and the right-angle directions when the impinging alpha particle has various

energies up to ten million volts. These results are plotted in the inset graph where both the horizontal and vertical axes represent energy in million volts.

Consequently, if one wishes to know how energetically protons would be emitted at right angles when eight-million-volt

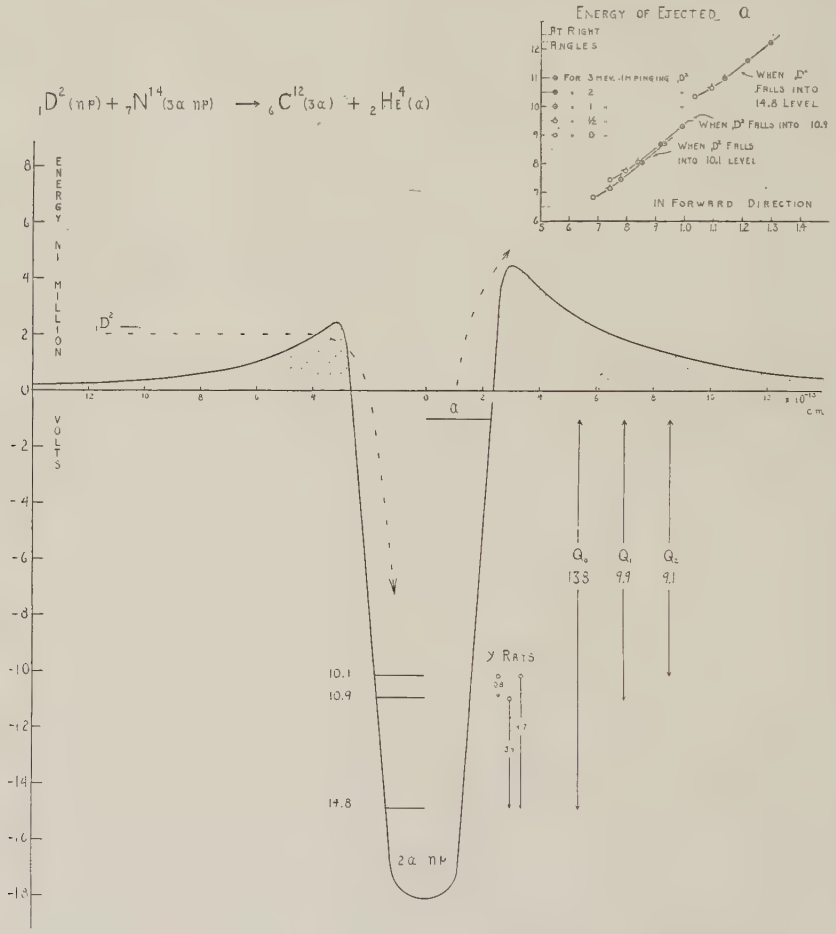

FIG. 4. Deuterons on Nitrogen.

alpha particles bombard boron, one can immediately see from the inset graph that there will be an eight-million-volt proton group if the alpha particles fall into the lowest level, or a 3.4-million-volt group if the alpha particles fall into the highest level. For protons emitted in the forward direction these two

numbers would be changed to 10.3 and 4.9, respectively. In general for a given alpha-particle energy, there are four proton groups emitted, since there are four levels into which the alpha particle may fall. The number in parentheses opposite each of these levels represents the relative chance that the alpha particle falls to that particular level.

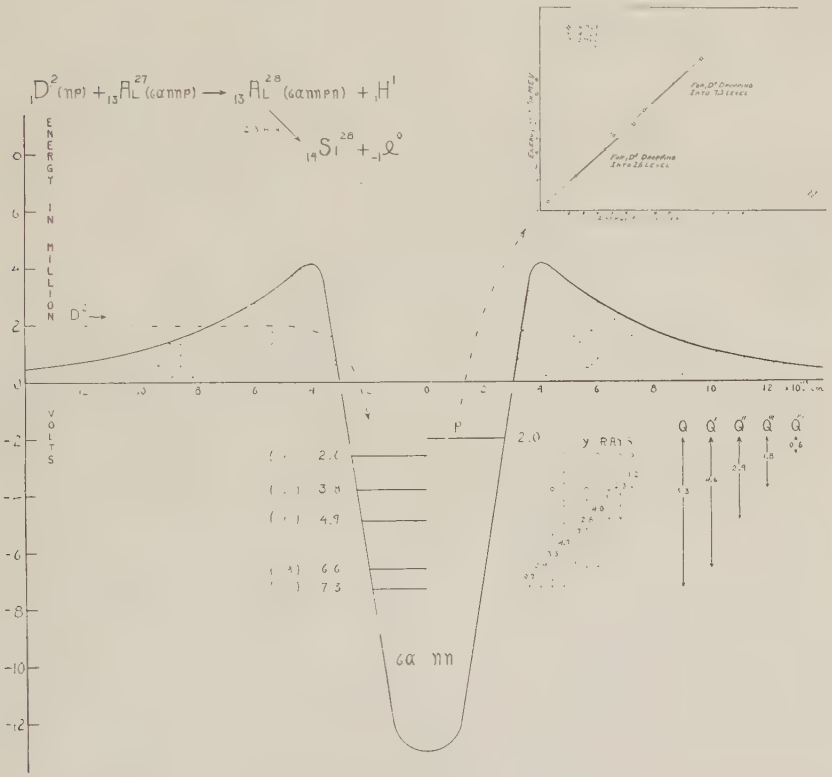

FIG. 5. Deuterons on Aluminum.

It seems to be true in this reaction as well as in most others that the impinging particle infrequently falls to the lowest level or ground level of the nucleus (10). When the alpha particle falls into a level other than the ground level the nucleus is thereby left in an excited state and later, perhaps in 10^{-20} sec., the alpha particle continues on down to the ground level. The energy difference is emitted as gamma ray. The possible gamma-ray energies are shown on the right side opposite the nuclear energy levels. In Fig. 1 all the transitions are dotted,

indicating that the expected gamma rays have not yet been observed. In some of the other figures gamma rays have been observed and are drawn in full line.

The true transmutation energy Q can be checked from the individual masses. For example, before transmutation

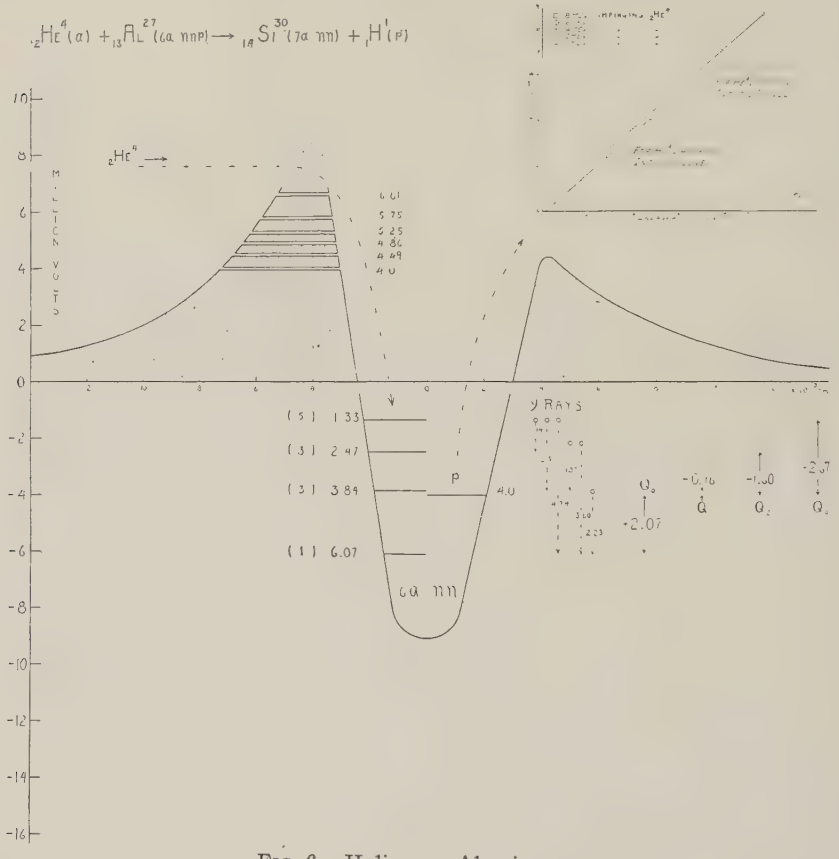

FIG. 6. Helium on Aluminum.

4.00336 + 10.0146 = 14.01796; after transmutation 13.0069 + 1.00807 = 14.01497. The decrease in mass is 0.00299. Using the Einstein mass-energy relation mentioned previously, this decrease in mass must now appear in the form of energy and in this case corresponds to 2.8 million volts of energy. This value is in only fair agreement with the observed energy gain of 3.1 million volts as shown by Q in the figure.

Only for alpha-particle bombardment does the potential barrier frequently exhibit a peculiar channeled structure. Through these channels (see also Fig. 6) the alpha particle

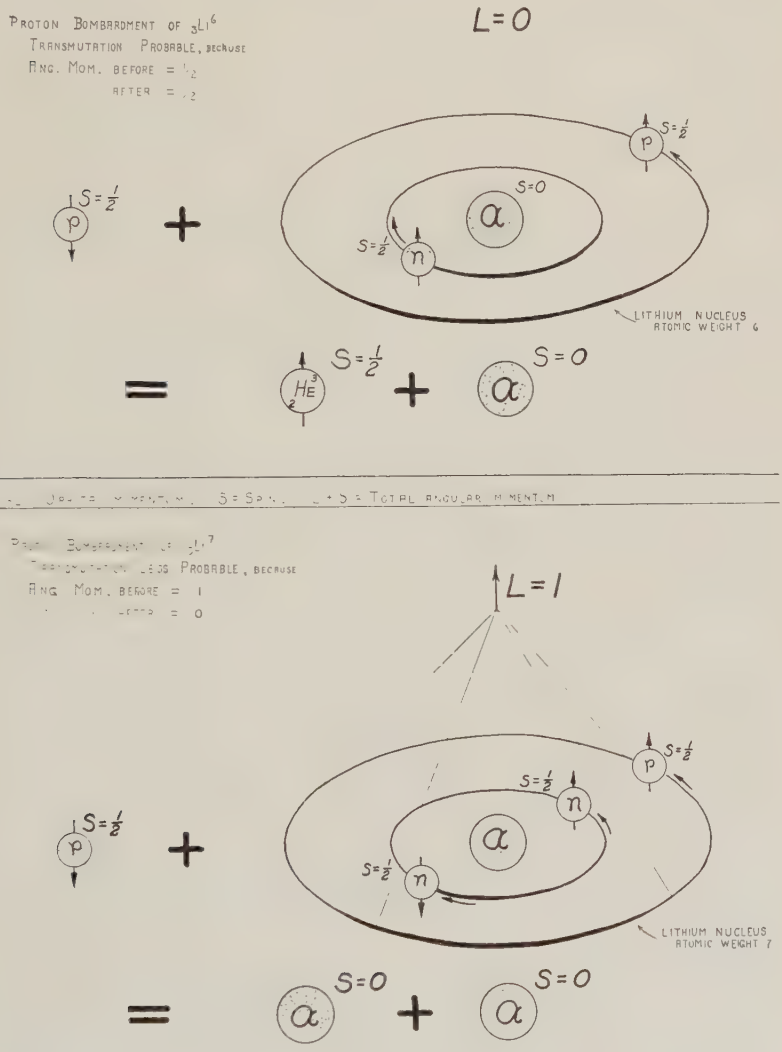

FIG. 7. Transmutation probabilities for protons on lithium 6, and on lithium 7.

seems to pass easily and the probability of a nuclear transmutation by alpha particles bombarding the nucleus with these particular energies is thereby greatly enhanced (11).

Fig. 2 shows the energy-level diagram (one of three) of an alpha particle itself and the large number of gamma rays observed (12). Notice how narrow and deep this nucleus is compared to the aluminum nucleus of Fig. 5.

NUCLEAR SPINS

So far we have used, although not explicitly expressed, three of the four conservation laws of nuclear physics. These laws are:

a). Conservation of electric charge.
b). Conservation of mass-energy.
c). Conservation of momentum.
d). Conservation of angular momentum.

The conservation of angular momentum is useful in explaining why some reactions are more probable than others (13). For example, consider Fig. 7 in which for proton bombardment the disintegration of lithium, atomic weight 6 (upper half of figure), is shown to be more probable than the disintegration of lithium, atomic weight 7 (lower half of figure). Assuming lithium, atomic weight 6, to consist of an alpha particle, a proton and neutron as shown, the total nuclear angular momentum is therefore $\frac{1}{2} + \frac{1}{2} = 1$. A proton with spin $\frac{1}{2}$ gives a resultant angular momentum before disintegration of $1 - \frac{1}{2} = \frac{1}{2}$, which is equal to the angular momentum after disintegration, $\frac{1}{2} + 0 = \frac{1}{2}$. This equality does not hold in the lower half of the figure, however, since before disintegration the total nuclear angular momentum is $(1 + \frac{1}{2} - \frac{1}{2} + \frac{1}{2}) - \frac{1}{2} = 1$ and after disintegration the angular momentum is $0 + 0 = 0$. The former reaction is about 30 times more probable than the latter. If sometimes, however, one of the alpha particles in the latter reaction is left in an excited state as indicated in Fig. 2, then the considerations just mentioned probably will not apply.

In closing, a word of caution should be said in regard to the tables and the figures presented here. They should not be read too closely or interpreted too literally because changes are being made from time to time in the data and in the interpretation of the data.

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DEUTERIUM AS A RESEARCH TOOL IN THE PHYSICAL AND BIOLOGICAL SCIENCES

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Ohio State University

The discovery (1) of deuterium and the production of "heavy water," its chief compound, in a nearly pure state (2), are among the more important scientific achievements of recent years. In less than two years from the production of heavy water in nearly pure condition over three hundred papers reporting investigations *on* or *with* deuterium have appeared in scientific journals. While most of these investigations have been of a physical or chemical nature significant results have been reported in investigations of biological character. It is probable that the principal role of deuterium, in future research in all of these fields, will be more that of a research tool than as an object of investigation.

Deuterium is not a new chemical element, as the name might imply, but is a special variety of hydrogen atom. It differs from the ordinary (or light) hydrogen, chiefly, in mass. The atomic weight of the ordinary hydrogen is *one* while that of deuterium, or heavy hydrogen, is *two*. It resembles the ordinary hydrogen atom in possessing just one unit of positive charge on its nucleus (equal to the number of electrons in the neutral atom) and it is this latter property which determines the chemical character of an atom, and hence its position in the family of elements. The existence of atoms which differ in mass although alike in nuclear charge is common among the elements, and atomic species which are related in this manner are called isotopes. Isotopes are very difficult to separate, because they are so nearly identical in chemical behavior. Only with hydrogen in recent months have isotopic separations on a moderate scale been at all successful. The fact that this has been accomplished rather readily has made the special name, *deuterium*, advisable.

The chemistry of deuterium is, in the main, that of ordinary hydrogen. It is thus possible to have any of the hydrogen bearing compounds, so numerous in Chemistry, with one or more deuterium atoms replacing a corresponding number of ordinary hydrogen atoms. With water this leads to the two

possibilities HOD (D is the symbol which chemists employ to represent an atom of deuterium) and DOD. Pure "heavy water" consists of DOD alone, while heavy water of less than 100% purity consists of HOH, HOD, and DOD mixed in proportions which depend on the relative numbers of H and of D atoms in the mixture. In like manner three "heavy" ammonias—NH_2D, NHD_2 and ND_3—are possible and numerous deuterium derivatives of such molecules as benzene, C_6H_6; ethyl alcohol, C_2H_5OH; etc., can be produced.

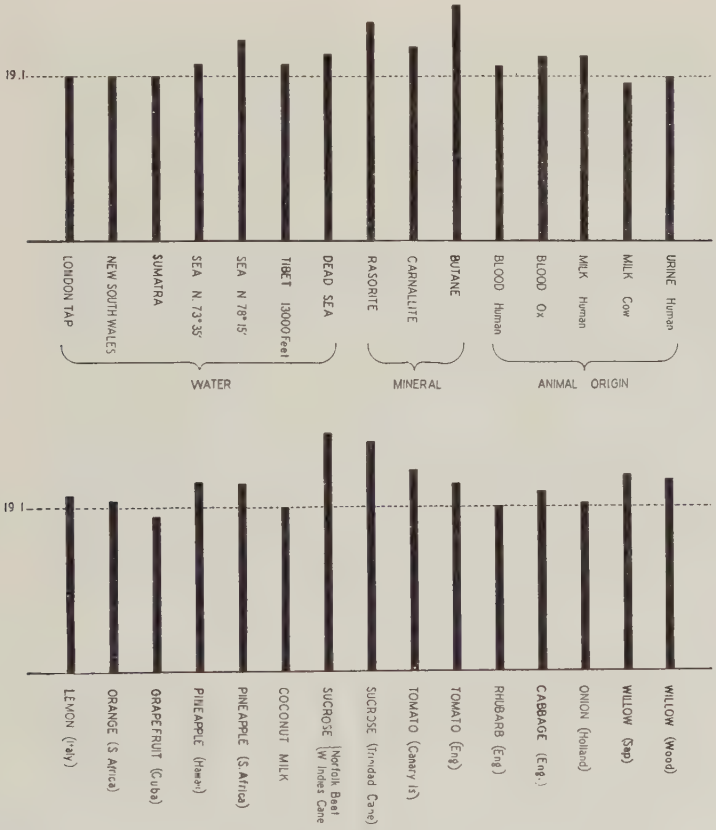


FIG. 1. (*Upper.*) Deuterium Content of Water from Natural Mineral and Animal Sources (relative to ordinary water).

FIG. 2. (*Lower.*) Deuterium Content of Water Obtained from Various Vegetable Sources (relative to ordinary water).

Replacement of light hydrogen in a molecule, by deuterium, necessarily results in an increase in the molecular weight—one unit for each replacement. Thus, for the respective molecules H_2O, HDO and D_2O molecular weights are 18, 19 and 20.

Molecular *volumes* are scarcely influenced by the replacements. As a result the *densities* of deuterium compounds are higher than for the corresponding compounds of ordinary hydrogen, and are in proportion to the molecular weights. The density of pure heavy water is very close to (20/18) times that of ordinary water and for less than 100% purity the density is a nearly linear function of the deuterium content. This provides one of the most convenient, as well as most accurate, ways of analyzing a sample of water for its deuterium content.

Deuterium exists in natural ground water to the extent of one D atom to about every 5800 H atoms (3) and contributes, through its presence, about 19.1×10^{-3} milligrams to the weight of each cubic centimeter of water. This proportion of D to H atoms is maintained, to a first approximation, in other natural sources but careful analyses reveal definite changes in the ratio which are characteristic of the nature of the source. The proportions of deuterium in waters derived from several mineral, vegetable and animal origins (4, 5, 6) is represented graphically in Figures 1 and 2 in which the dotted line (norm) corresponds to the deuterium content of normal ground water. Some of these variations in the ratio must be attributed to partial separations of the isotopes during chemical changes within living organisms—others to physical processes, such as evaporation.

The chemist does not *make* either deuterium or heavy water in the strict sense but is able to extract it from those natural sources—principally water—in which it already exists in low proportion. The high cost of heavy water is a consequence of the high cost of extraction and is not due to limitation of the gross supply. Indeed the potential supply of deuterium is inexhaustible. A simple calculation, based on the ratio of 1 D atom to every 5800 H atoms, reveals that enough deuterium is present in the circle of ocean visible from the deck of a large ocean liner to yield nearly one cubic mile of pure heavy water. By the cheapest process yet developed the cost of extracting this quantity of D_2O would require a ten billion dollar annual expenditure for a period of 800,000 years. There is little doubt that the cost of extraction will continue to drop, as it has done rapidly during the past two years. In this period the cost of pure D_2O has dropped from $150 per gram to about $2.00 per gram.

Heavy water is ordinarily produced by a process of electrolysis. Figures 3, 4, and 5 are views of portions of the

FIG. 3. Main Section of the Heavy Water Plant at the Ohio State University; 1000 water-cooled cells reduce 100 gallons of dilute heavy water from commercial cells, per week, to about 11 liters of 1% D_2O.

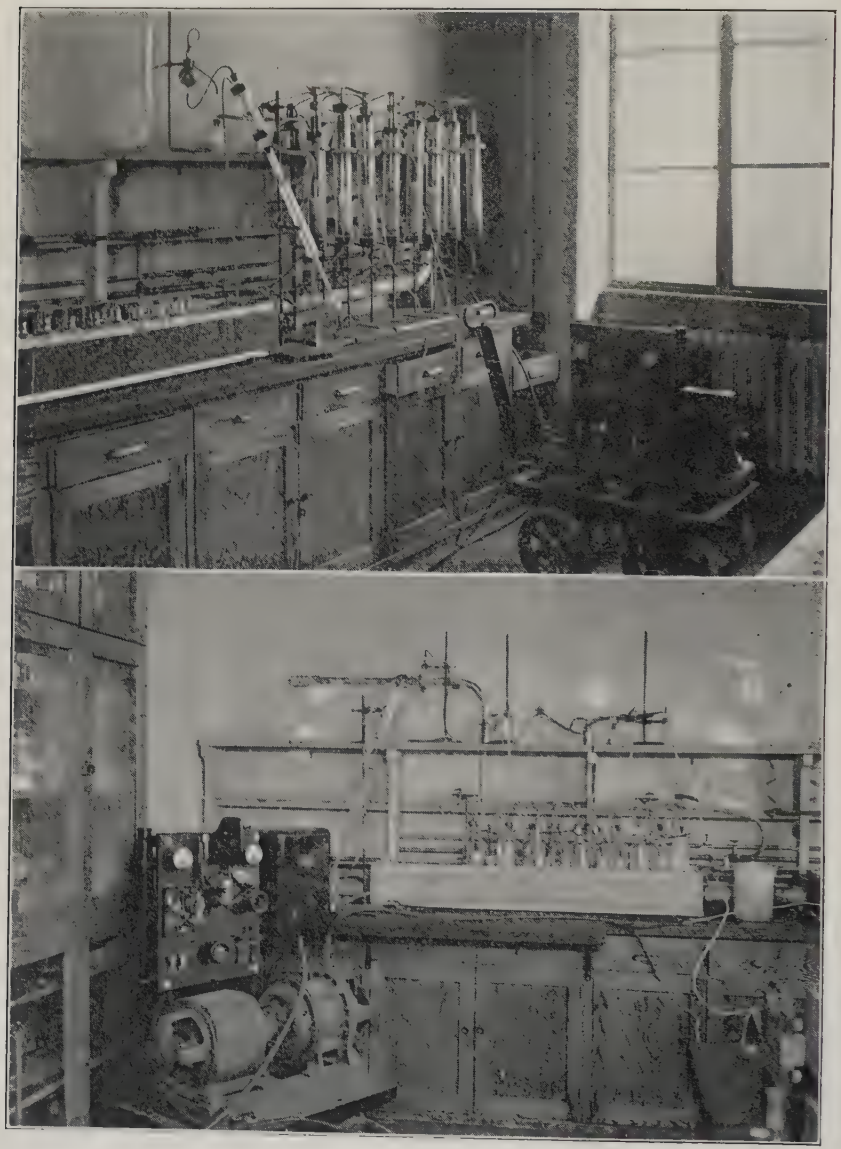


FIG. 4. (*Upper.*) Intermediate Section of the Heavy Water Plant at the Ohio State University. These cells of high current carrying capacity reduce the output of the Main Section to 10% D_2O. A burner and condenser for recombination of the electrolytic gases is shown in the foreground.

FIG. 5. (*Lower.*) Final Section of the Heavy Water Plant at the Ohio State University. These "test tube" cells reduce the output of the Intermediate Section to D_2O of concentration higher than 99%. The output is about 50 grams per week.

large heavy water plant constructed and operated at The Ohio State University,[1] which is capable of producing about fifty grams of pure D_2O per week at a cost of a little over $2.00 per gram. The use of the electrolytic process depends upon the fact that the H/D ratio in the hydrogen evolved in the electrolysis is 4 to 8 times larger than that in the electrolyte. As a consequence the concentration of deuterium in the residue increases as the electrolysis continues and approaches 100% as the volume of residue shrinks to zero. The efficiency of the process depends on the choice of electrodes and of electrolyte and on other conditions of operation.

Other methods may also be used to effect the extraction of deuterium. Distillation of water (7, 8) may in time replace the electrolytic process. Distillation of liquid hydrogen (1, 9) should be still more effective. Its principal hindrances are of an engineer-

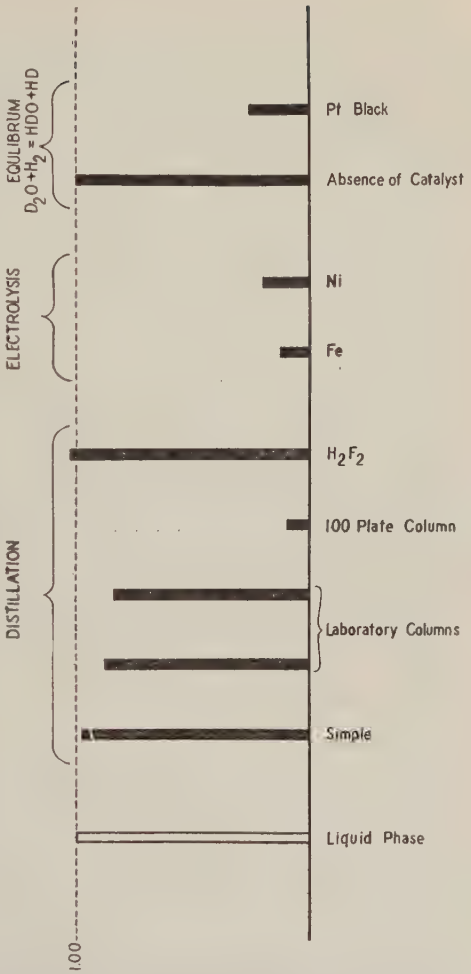


FIG. 6. Relative Efficiencies of Several Means of Separating Deuterium from the Lighter Isotope of Hydrogen. The heights of the vertical bars represent the deuterium content of the gas escaping from a liquid residue whose hydrogen is 1% deuterium.

[1]This plant was put into operation in March, 1934. The first and largest unit consists of approximately 1000 small water cooled cells constructed from ordinary 500 cc. wide-mouthed bottles closed with two-hole rubber stoppers and fitted with electrodes of Armco iron. The mixture of hydrogen and oxygen produced in the later stages of the electrolysis is allowed to recombine to reform water which is then electrolyzed over again, in an earlier stage of the plant, to recover the deuterium in the electrolytic gases. The raw material used in this plant was water taken from commercial electrolytic cells (D/H ratio, about 1/2000) and was furnished, free of charge, by the Capital City Products Co. of Columbus. The staff and students of the department of Chemical Engineering at

ing character and can, no doubt, be overcome. Diffusion (10) and desorption (11) processes and chemical reactions (12, 13) that liberate hydrogen or its gaseous compounds represent yet other ways of separating deuterium from its more plentiful isotope. Relative efficiencies of a number of these methods are

TABLE I

Comparison of Some Properties of Normal Water With Those of Pure Heavy Water (Collected from Various Sources)

	H_2O	D_2O
Molecular Weight	18	20
Specific Gravity	1.0000	1.1079
Freezing Point	0° C.	3.80
Boiling Point	100° C.	101.42
Refractive Index	1.33300	1.32828
Dielectric Constant	81.5	80.7
Viscosity (30°)	8.00	9.72
Heat of Fusion	1435	1510
Heat of Vaporization	10484	10743
Ionization Constant	1×10^{-14}	0.3×10^{-14}

Vapor Pressure Ratio (pH_2O/pD_2O) ≈ 1.05 at 100° C.
Solvent Action Toward Salts—Solubility in D_2O 80% to 90% of that in H_2O.

TABLE II

Comparison of Some Properties of Molecular Hydrogen With Those of Pure Deuterium (Collected from Various Sources)

	H_2	D_2
Molecular Weight	2.0156	4.027
Freezing Point	13.92° K.	18.58° K.
Boiling Point	20.38° K.	23.5° K.
Heat of Fusion	28.0 cal/mole	47.0 cal/mole
Heat of Vaporization	217.7 cal/mole	308.3 cal/mole
Heat of Dissociation (into atoms)	102,800 cal/mole	104,425 cal/mole
Viscosity (gas at 30° C.)	916 c. g. s. units	129.5

illustrated in Figure 6. Indeed, it is difficult to find a process —physical or chemical—in which measurable change in the proportion of the hydrogen isotopes is not produced.

The Ohio State University assisted in the preliminary preparations by distilling the water out of the strong alkaline electrolyte which was used in the commercial cells, and preparing fresh electrolyte for return to the Capital City Products Co. Dr. J. H. Koffolt was in immediate charge of this operation. The construction and operation of the heavy water plant was carried out with the assistance of Mr. W. H. Hall, graduate student in the Department of Chemistry.

Table I is a comparison of a few of the properties of pure D_2O with those of H_2O.

Table II is a similar comparison of molecular hydrogen with molecular deuterium, and Figure 7 illustrates the heat capacity vs. temperature curves (14) of the respective molecules H_2, HD and D_2. Other compounds of hydrogen would exhibit similar variation in properties from those of their deuterium analogues. In general the differences in properties are greatest at low temperatures.

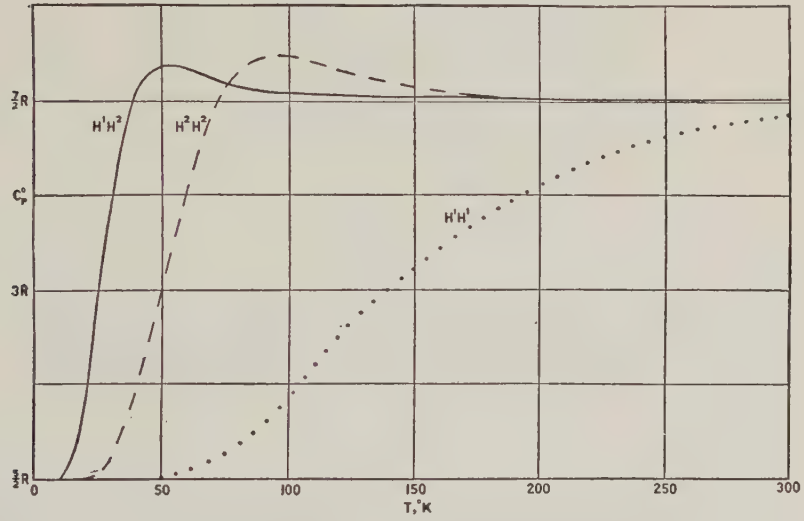


FIG. 7. Heat Capacity Curves (non equilibrium mixtures with respect to ortho-para states of D_2 and H_2) of H_2, HD and D_2. (After Johnston and Long, J. Chem. Physics **2**, 389 [1934].)

The utility of deuterium in research depends, in the majority of cases, directly or indirectly on variations such as are exhibited in Tables I and II or on quantitative estimates of the presence of deuterium, which utilize certain of these properties. Measurements of specific gravity (21, 15) or of refractive index (15, 16, 17) of carefully purified samples of water constitute the more usual and more accurate means of analyzing for deuterium but the measurement of the thermal conductivity (18) of gaseous mixtures of hydrogen and deuterium is not infrequently employed. The latter method is based on the differences in specific heat (Figure 7) on which thermal conductivity is dependent, and possesses the advantage that very tiny amounts of gas may be analyzed by this method.

It is possible, in this address, to illustrate the use of deuterium as a tool in solving fundamental problems in scattered fields for only a few of the cases in which it has been so employed. But these can be chosen to illustrate its wide range of applicability. For convenience I shall discuss these under the several headings of Physics, Chemistry, and the Biological Sciences.

PHYSICS

Modern Physics is concerned primarily with the structure of matter. This includes both the atom and the molecule and, more recently, attention has been turned to the tiny and almost inaccessible nucleus of the atom. Great progress has been made in nuclear investigations since the discovery of deuterium and the use of the deuteron, its own nucleus, to bombard the nuclei of heavier atoms or to produce *neutron* beams (19) of high intensity for the bombarding projectiles. This has resulted, in the brief space of two years, in the production of new radioactive substances (20) which possess utility as radioactive indicators in various types of chemical investigations and are sufficiently active to compete with natural radioactive elements in the treatment of disease. Continued progress in this field of nuclear investigation—with deuterium an indispensable tool—must inevitably result in a nuclear chemistry of far-reaching consequences and may unlock vast new storehouses of energy.

The greatest impetus to modern physical research came in Bohr's well known theory of the hydrogen atom. Although this theory broke down, in its details, when applied to the heavier elements it yielded, with Sommerfeld's modification, good quantitative agreement with all experimental observations of hydrogen itself. This theory of Bohr predicts very definitely the positions of lines in the spectrum of atomic deuterium. These lines should appear slightly shifted from the corresponding lines of ordinary hydrogen and the amount of the shift is calculable in terms of the theory. It is therefore of considerable interest that the discovery (1) of deuterium was based on the presence of weak lines at the positions calculated for an hydrogen atom of mass two (cf. Figure 8) and that further research (2) with much richer mixtures of deuterium and with higher dispersion in the optical systems (cf. Figure 9) were in good accord with the quantitative aspects of the simple Bohr theory. One

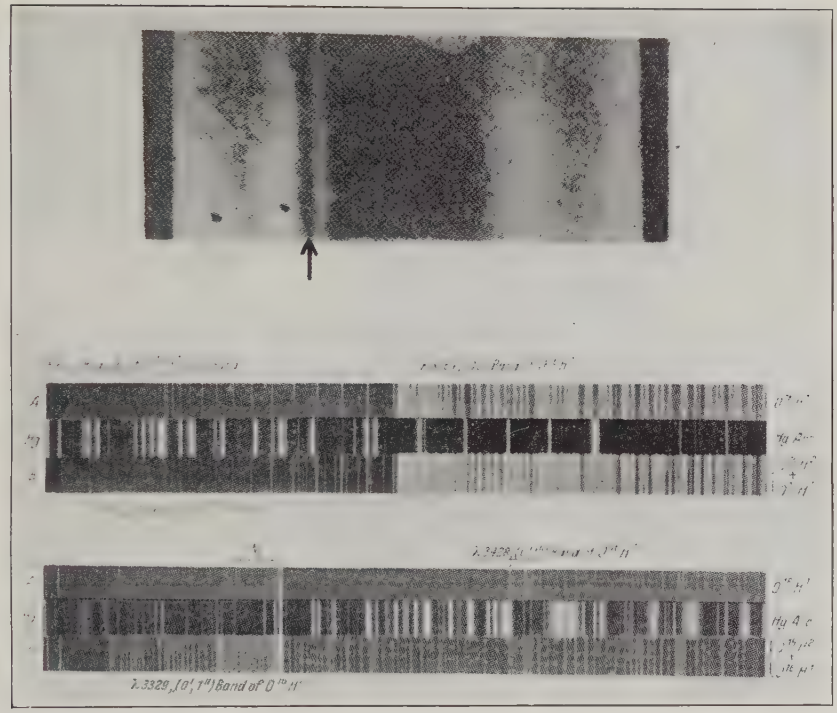


FIG. 8. (*Upper.*) Isotope Shift in one of the Balmer lines of Hydrogen (after Urey, Brickwedde and Murphy, Phys. Rev. **40,** 1 [1932]). The narrow line above the arrow is due to the D atom in hydrogen gas enriched slightly in deuterium by evaporation of liquid hydrogen.

FIG. 10. (*Lower.*) Isotope Effect in the Spectrum of OH (after Johnston and Dawson, Naturwissenschaften **21,** 495 [1933]). (The center strips in each panel are spectra of the mercury arc used for reference.)

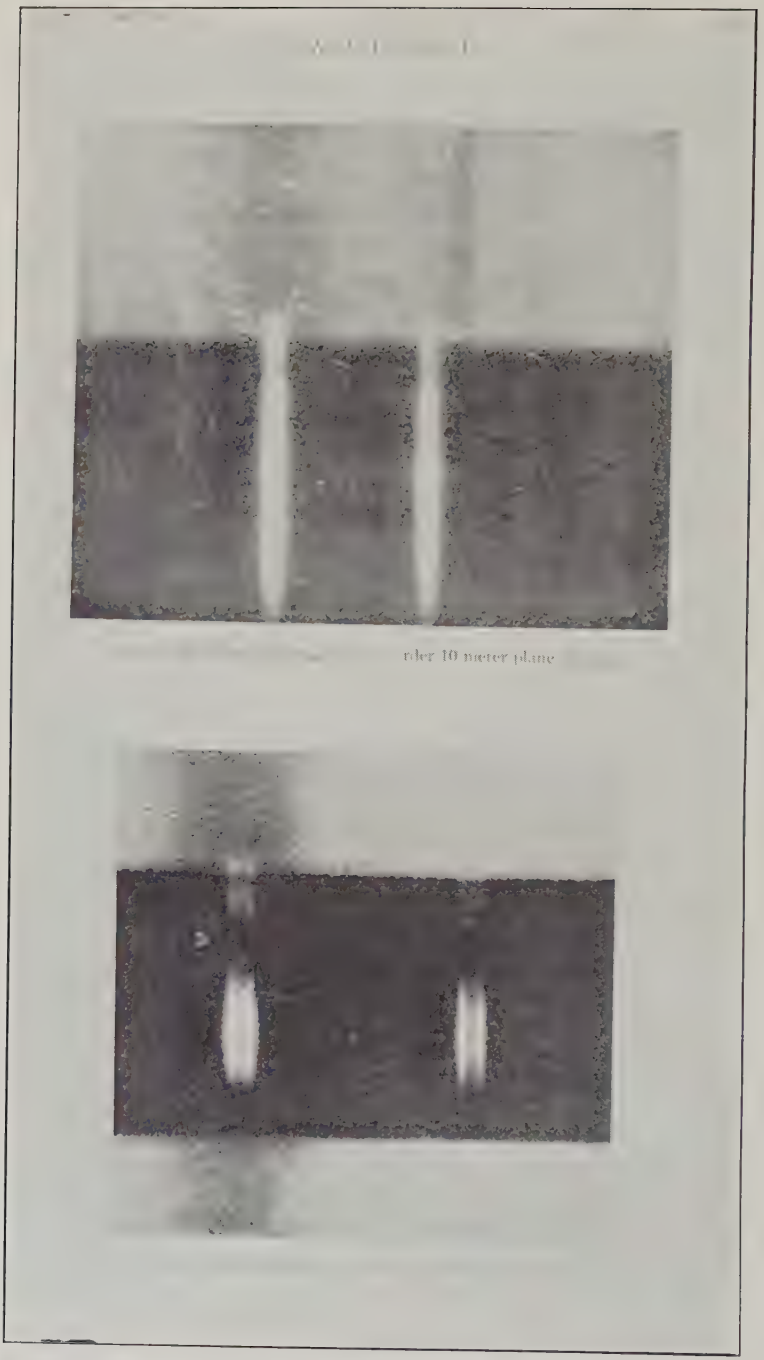


FIG. 9. Wider Separation of the Isotope Lines due to atomic hydrogen with a nearly 50–50 mixture of H_2 and D_2. (After G. N. Lewis and F. H. Spedding, Phys. Rev. **43**, 964 [1933].) Note the sharper resolution of the doublet lines for one of the doublets on the lower photograph. This is the D line (these "lines" are really multiple) and is better resolved because of the smaller Doppler effect for the heavier atom.

quantitative feature of Sommerfeld's modified form of the Bohr theory, which involves the resolution of apparent single lines into several "fine structure" components, could never be tested adequately for ordinary hydrogen—due to overlapping and blurring of the component lines caused by the high velocity of hydrogen atoms moving in the region of the exciting discharge (Doppler effect). Simple gas kinetic theory indicates that the atomic velocities, and hence the blurring, should be less with deuterium than with hydrogen, so that this quantitative aspect of the Bohr-Sommerfeld-spin theory might now be subject to test. This is found to be true and investigations (22, 23) which may prove of considerable help in unravelling difficult aspects of atomic structure theory are in progress.

The structure of the molecule and the nature and magnitude of the binding forces which hold atoms together in individual molecules is a realm of great interest to chemists as well as to physicists. A great deal of progress has been made in this field during the past decade but there are still many problems unsolved even for the case of comparatively simple diatomic molecules. Knowledge in this field has come mainly through the study and interpretation of molecular spectra, commonly referred to as "band spectra," due to their characteristic appearance at low dispersion.

Errors in interpretation have arisen, not infrequently in the past, through failure to correctly identify the chemical nature of the molecule responsible for a spectrum. When it is possible to replace one atom in the responsible molecule by its isotope every line in its spectrum is shifted and the shifts on individual lines are calculable by theory. The use of this so-called isotope effect can therefore be employed sometimes to identify the chemical nature of the molecule responsible for a spectrum since the theoretical calculation of the shift depends on the correct chemical identification. An example of this kind (24) is illustrated in Figure 10. The spectra reproduced in this figure are emitted by water vapor through which an electrical discharge of high potential is passing and were variously assigned, in the early years of study, to the H_2O molecule and to the O_2 molecule. It was later interpreted as due to the unfamiliar gaseous molecule OH and these photographs obtained by passing an electrical discharge through a mixture of ordinary and heavy water definitely confirms this latter assignment. The RR lines whose positions are indicated on the bottom of

the (0, 0) band photograph and the λ 3329 band on the lower photograph fall very close to the positions calculated for an OD molecule. In this particular case the chemical identity of the molecule responsible for the water vapor spectrum was satisfactorily established beforehand but in the case of other molecules containing hydrogen—particularly molecules with more than two atoms—the isotope shift, with deuterium substitution, provides a means both of molecular identification and of the correct assignment of vibrational quantum numbers. Clues to the explanation of difficult points in the theoretical interpretation of complex molecular spectra and of the correct calculation of inner forces are also provided by exact quantitative measurement of the large isotope shifts in deuterium compounds and their departure from simple theory.

CHEMISTRY

Chemically, deuterium resembles ordinary hydrogen. However, this resemblance is not complete and small differences are found in equilibrium constants and, in several instances, rather large differences in reaction velocities. Perhaps the most important change in an equilibrium constant is that of the ionization constant of water to yield hydrogen and hydroxyl ions. For pure heavy water this important constant is about one-third (cf. Table I) of that for ordinary water. which indicates that the degree of ionization of D_2O is only 60% of that of H_2O. In a like manner weak acids or bases dissolved in D_2O ionize to a lesser degree (25) than in H_2O. The effect of these changes in important ionic equilibria is to change pH values and otherwise modify the character of certain ionic reactions in solution. Equilibrium changes of this character no doubt contribute to the biological effects of heavy water. A number of gas and gas-liquid phase equilibria whose constants show the isotopic influence on the reactivity have also been investigated, (26, 27, 28, 29, 14).

An interesting and important example of a chemical difference between deuterium and hydrogen compounds is furnished in displacement reactions of metals with water or with acid to yield gaseous hydrogen and in similar reactions which liberate gaseous compounds of hydrogen. The first examples of this sort were reported by A. and L. Farkas (12) and by Davis and Johnston (13) who observed, independently, that the gas liberated in reactions of this character, from solutions

which were a mixture of H_2O and D_2O, contained a lower proportion of deuterium than the solution from which it was liberated. The deuterium impoverishment in the gas stream is sometimes quite marked. The extent of this impoverishment is highly reproducible and is almost independent of the nature of the solution but is dependent on the surface character of the reacting metal. Figure 11 (30) illustrates the extent of this impoverishment for several reactions of this character. To what extent this effect may be attributed to changes in equilibrium constants and to what extent to differences in the reaction velocity of the heavy and light molecules or ions in the mixture is not yet known.

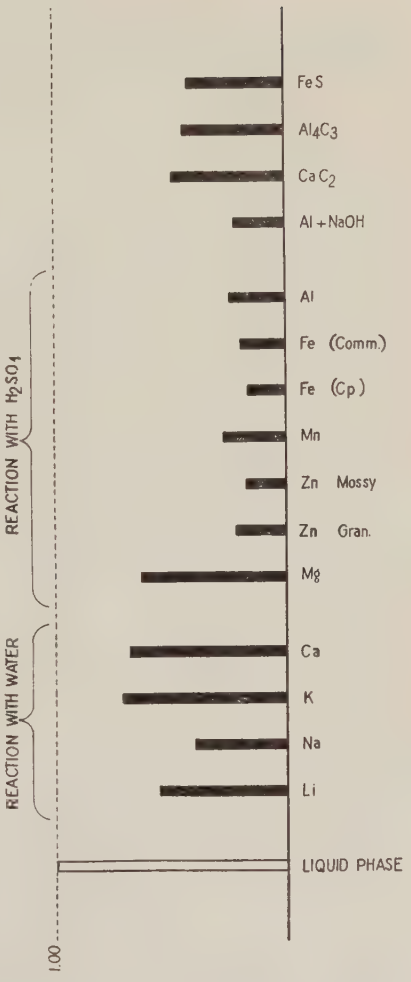


FIG. 11. Efficiency of several chemical replacement reactions in the separation of the hydrogen isotopes. The heights of the bars represent the deuterium contents of gas escaping from a liquid residue whose hydrogen is 1% deuterium. (Unpublished work of H. L. Johnston and C. O. Davis.)

A very simple type of reaction with isotopic atoms which is of great service in indicating the tightness of binding of various linkages and in studying chemical kinetics is of the type known as an "exchange" reaction. This type of reaction was first observed by Lewis (31) who observed that the hydrogen atoms in ammonia gas which was bubbled through a dilute heavy water solution "exchanged" with the hydrogen and deuterium atoms in the water (evidenced by the deuterium atom exchange) so that the deuterium concentration of the escaping ammonia approached that of the residual water. The mechanism of this exchange is represented by the following reaction:

$$NH_3 + HDO = NH_2D + H_2O \quad (1)$$

which probably goes through the steps

$$NH_3 + HDO \rightleftharpoons NH_3DOH \rightleftharpoons NH_2D + H_2O \quad (1a)$$
$$(\text{or } NH_3 + HDO)$$
$$\text{or } \rightleftharpoons NH_4OD \rightleftharpoons NH_3 + HDO.$$

With water containing a high concentration of deuterium, reaction of NH_2D may continue by a mechanism corresponding to (1a) until two or, finally, all three of the hydrogens of the original amomnia are exchanged with deuterium in the water. Likewise all four hydrogens in ammonium ion (NH_4^+) (32) and the acid hydrogen in strong acids (33) exhibit rapid exchange with water.

Interesting examples of exchange reactions between water and hydrogen of various linkages in organic compounds are shown in Table III, which is taken from the extensive review article of Urey and Teal (34).

TABLE III

Exchange Reactions Between Water and Organic Compounds

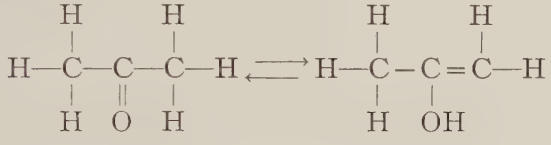
Compound	Observation	Reference
CH_3COONa	No exchange	(35)
CH_3COOH	1 hydrogen atom exchanges rapidly	(36)
C_6H_6	No exchange	(35)
CH_3CHO	1 hydrogen atom exchanges slowly	(35)
CH_2O	2 hydrogen atoms exchange slowly	(35)
CH_3COCH_3	Very slow exchange in neutral solution. Faster exchange in acid solution. Very fast exchange of all hydrogens in alkaline solution	(35, 37, 38)
$CH_3COCH_2COCH_3$	All hydrogens exchange	(35)
C_2H_2	Exchange in alkaline solution	(39)
Glucose and cane sugar	Hydroxyl hydrogen exchange immediately	(32)
$(CH_2OH)_2$	One-third of hydrogens exchange immediately	(33)
Egg Albumen	All hydrogens attached to N. atoms exchange.	(40)
Cellulose	All hydroxyl hydrogens exchange	(40)

The several investigations included in this table show the immobility of hydrogen attached directly to carbon except where keto-enol transformations are possible; the high mobility of carboxyl, hydroxyl and amino hydrogen and the low mobility of aldehydo hydrogen. The exchange with acetylene in alkaline solution provides evidence for the weak acidic character of

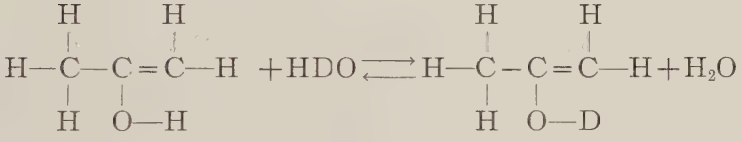
acetylene in aqueous solution, for which there was some evidence from other sources. This probably results from an equilibrium of the type.

$$C_2H_2 \rightleftharpoons C_2H^- + H^+ \qquad (2)$$

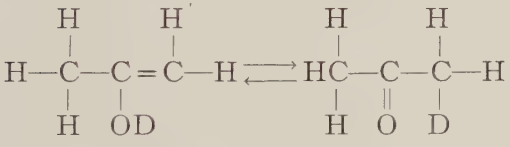
The exchange in acetone, in contrast to the resistance to exchange by methyl hydrogen in acetates and in acetic acid, is evidence in favor of the keto-enol transformation in acetone—a question which has been in dispute on the basis of direct chemical evidence alone. The exchange probably occurs with the hydroxyl hydrogen of the enolic form of the molecule and follows the following set of reactions.



(3a)



(3b)

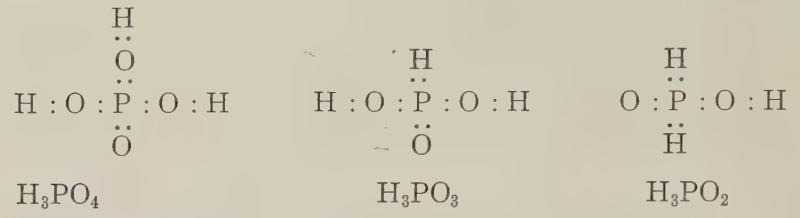


(3c)

This process may be repeated, in water of high deuterium content, until all six hydrogens of the acetone are replaced by deuterium.

A good example of the application of deuterium exchange reaction to problems of molecular structure is illustrated by the oxygen acids of phosphorus. Complete exchange of the three hydrogens in ortho phosphoric acid, H_3PO_4, takes place in line with the chemical expectation of complete hydrogen replacement to form the normal salts (e. g., Na_3PO_4) and illustrates that all three hydrogens in this molecule are attached by a mobile type of linkage. Two of the three hydrogens exchange in ortho-phosphorus acid (H_3PO_3) and only one of the three in hypo-phosphorus acid (H_3PO_2) (33). The immobility of a portion of the hydrogen in the latter acids points to a different type of linkage for the immobile atoms than that prevalent in

H_3PO_4. The structure of the latter molecule is characteristic of strong oxygen acids, such as sulphuric, and involves hydrogen linked to phosphorus, *through oxygen*. There are apparently only two such linkages in the H_3PO_3 molecule and only one such linkage in H_3PO_2. The probable structures of the three molecules based on the exchange phenomena is represented below.



H_3PO_4 H_3PO_3 H_3PO_2

The dots represent the position of bonding electrons which hold the atoms together. The immobile hydrogens are linked directly to phosphorus in a manner analogous to the immobile linkage direct to carbon in organic molecules. Latimer and Rodebush have previously postulated these structures for H_3PO_3 and H_3PO_2 on the basis of direct chemical evidence.

The most important results obtained through the use of deuterium in chemical research have been through its use as a tracer in chemical processes. The introduction of deuterium into a molecule provides a way of "labelling" the molecule which does not appreciably alter its normal chemical behavior. If deuterium be introduced at a definite position in an organic molecule the *normal* behavior of an hydrogen atom attached at that position, or of the group of which it is a constituent, during a chemical reaction, may be determined by tracing the deuterium through the products of the reaction. One excellent example of this use is in connection with determination of the mechanism by which ammonia decomposes in ultraviolet light. Stoichiometrically, the reaction is

$$2\,NH_3 + \text{ultraviolet light} = N_2 + 3H_2 \qquad (4)$$

and the first step is thought to be

$$NH_3 + \text{light} = NH_2 + H \qquad (4a)$$

The principal objection to this proposed mechanism is that only one-fourth as much NH_3 is decomposed for a given light absorption as is to be expected if this is the mechanism. This objection is over-ruled if it can be shown that the reverse

$$NH_2 + H = NH_3 \qquad (4b)$$

reaction can occur spontaneously. Taylor and Jungers (41) have demonstrated, with the aid of deuterium that reaction (4b) does take place. They accomplished this by introducing deuterium atoms (produced by impacts of suitably energized mercury atoms on D_2 molecules) into dry ammonia gas and observing, by means of the spectrograph, the presence of NH_2D, of NHD_2 and of ND_3 molecules in the gaseous mixture. In the absence of direct exchange (no exchange occurs between dry NH_3 and D_2 in the absence of a catalyst) reaction (4b) is the only apparent mechanism which can account for the introduction of the deuterium. (The introduction of more than one atom of deuterium must have come about through repetition of reaction (4a) on ammonia molecules into which deuterium was already introduced by reaction (4b).

An unexpected reaction between ethylene and hydrogen, which is no doubt typical of other organic molecules with one or more double bonds, has been observed by Farkas, Farkas and Rideal (42) through a study of the reaction between ethylene and deuterium on the surface of a nickel wire. These authors find that both reactions

$$C_2H_4 + D_2 = C_2H_4D_2 \qquad (5)$$

and

$$C_2H_4 + D_2 = C_2H_2D_2 + H_2 \qquad (6)$$

occur simultaneously and by independent processes. Reaction (5) is the analogue of direct hydrogenation of the unsaturated molecule and is expected. Reaction (6), which predominates at temperatures above 60°C, represents a loosening of the C-H bond at the catalyst surface. This loosening, with exchange of atoms between the ethylene and hydrogen molecules undoubtedly occurs in mixtures of double bonded compounds with ordinary hydrogenation but is revealed, for the first time, through the deuterium tracer. An exchange of similar character between deuterium and the hydrogen in saturated aliphatic molecules does not occur at low temperatures but, through the tracer action of deuterium, Taylor and coworkers (43) have recently found evidence for exchange between methane CH_4, and deuterium at 170° C, on a nickel catalyst. The significance of this discovery is that it provides evidence for the breakdown of methane into the fragments CH_3 and H on a nickel catalyst at a temperature two hundred degrees lower than it has been possible to detect it by other means.

A particularly important result, from a practical standpoint has come about through a study of the exchange reaction

$$H_2 + D_2 = 2HD \qquad (7)$$

This reaction does not occur at all at moderate temperatures in the absence of catalysts. But in the presence of certain catalysts which are effective in commercial hydrogenation processes Gould, Bleakney and Taylor (44) find that the reaction takes place at temperatures even as low as that of liquid air. This reaction can only take place through the formation of atoms on the catalyst surface and the probable mechanism by which this occurs is illustrated in Figure 12.

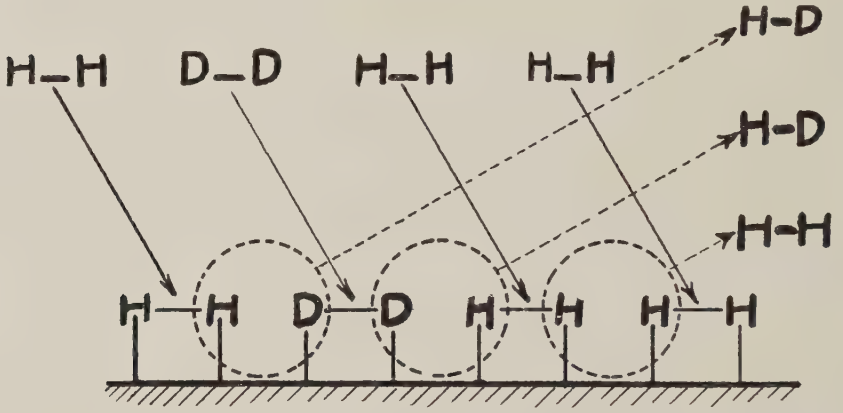


FIG. 12. Illustration of the probable manner in which the molecular bonds in H_2 and in D_2 are weakened on the surface of an hydrogenation catalyst so as to permit the re-pairing of atoms (or other rebonding of hydrogen atoms).

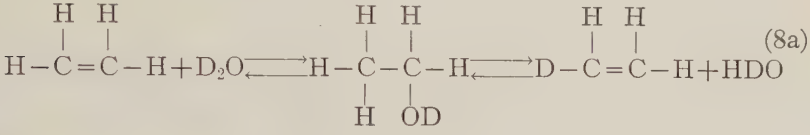
The figure is intended to show the way in which bonds established between the catalyst and the separate atoms weaken the bonds of atom to atom and permit return to the gas phase with an exchange of partners. This process—the loosening of hydrogen molecular bonds—is essential in many important industrial hydrogenation processes—such as the synthesis of ammonia from its elements. The experiments with deuterium show that the slow rate at which these commercial processes occur even at elevated temperatures is due to causes other than the loosening of the hydrogen bond, to which the slow reaction was previously attributed, and point the direction of future research.

The exchange reactions:

$$C_2H_4 + 2D_2O \rightleftharpoons C_2D_4 + 2H_2O \quad (8)$$

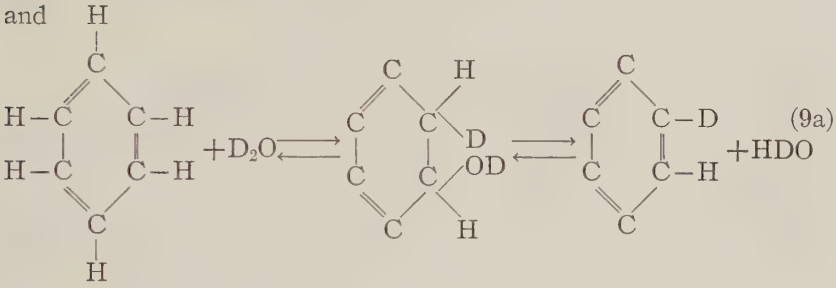
$$C_6H_6 + 3D_2O \rightleftharpoons C_6D_6 + 3H_2O \quad (9)$$

with liquid water occur only in the presence of sulfuric acid (45, 46). Polanyi (46) seeks to account for the influence of the acid by the mechanisms:



(8a)

and



(9a)

This proposal is the introduction of a water molecule into a double bond, in either case, and is the opposite of a dehydration process, for which sulfuric acid is very effective. Polanyi bases his proposal on the fact that a true catalyst promotes approach to an equilibrium condition from either direction. Further research will be necessary in this case to establish the true nature of the catalytic action of sulfuric acid but the possibility of some very interesting results in our understanding of the mechanism of catalysis is apparent.

Reaction velocities in processes which involve deuterium or its compounds generally differ from the velocities of the corresponding reactions with ordinary hydrogen. As a rule the effect of deuterium is to slow down the reaction. Figure 13 (47) illustrates this for the reaction of aluminum with sulfuric acid. In the case of certain of the simpler gaseous reactions it has been possible to correlate the velocity change, quantitatively, with the mechanism of the reaction. Thus for the reaction

$$H_2 + Br_2 = 2HBr \quad (10)$$

Bonhoeffer, Bach and Fajans (48) find that D_2 reacts five times more slowly than H_2 at 283° C. This is in good agreement with the 1600 calorie higher energy (Table II) required to dissociate D_2 for step (b) of the proposed mechanism

$$Br_2 = 2Br \tag{10a}$$

$$Br + H_2 = HBr + H \tag{10b}$$

$$H + Br_2 = HBr + Br \tag{10c}$$

$$2Br = Br_2 \tag{10d}$$

in which (10b) and (10c) constitute a "chain" broken by (10d), and (10b) is the rate controlling step in the mechanism. Melville (49) finds that the slower reaction rates of deuterium,

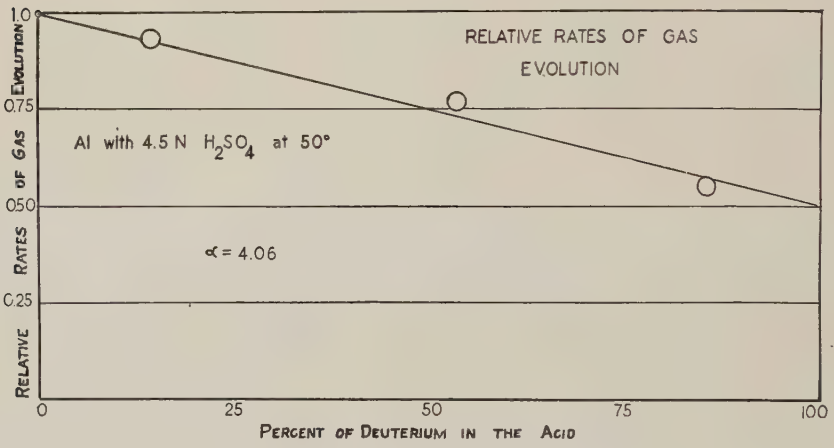


FIG. 13. Influence of Deuterium on the rate of reaction between Zinc and Sulfuric Acid. (Unpublished work of H. L. Johnston).

than of hydrogen, toward both O_2 and N_2O at the surface of a nickel catalyst are likewise in quantitative agreement with the difference in energies required to bind D and H atoms, respectively, to the catalyst surface.

A few examples have been found in which reaction rates with deuterium compounds proceed more rapidly than with ordinary hydrogen compounds (50, 51).

The use of deuterium as a tool in organic structural chemistry and mechanism—in which it should prove useful both as a tracer and as an indicator of the presence of groups which contain mobile hydrogen—is, as yet, scarcely touched.

BIOLOGY

Water with a high content of deuterium possesses a direct influence on certain physiological processes. Lewis (52) found that tobacco seeds fail to germinate in 80% heavy water (an excellent illustration of the results of this experiment, together with the 100% germination shown by controls, is given in the reference) and that the action of the heavy water is to inhibit or retard germination rather than to render the seed sterile (53). A similar inhibitory effect was observed for lupino seeds in dilute heavy water (54) but no effect whatever was observed on the germination of wheat (55). Taylor and his associates (56) have shown that high concentration of D_2O are fatal to tadpoles and to guppies within a few minutes and to lower organisms such as flatworms and protozoa within a few hours. Experiments of this sort have been frequently repeated by Taylor (57) with care exercised to eliminate every extraneous cause of the lethal action and the results reported in the original paper have been, each time, confirmed. Internal administration of nearly pure heavy water to a mouse (53), while not lethal in effect, did produce decided physiological reaction. This consisted of an increase in thirst and in a high excitability resembling intoxication.

The manner in which water with a high deuterium content is responsible for physiological changes is not known although there are several possibilities in view of the modifications of physical and chemical properties of water itself. These include: the change in the ionization constant of water and in the ionization and hydrolysis constants of dissolved electrolytes; unequal changes in the rate constants of various interdependent biochemical reactions taking place in the organism; the hydroscopic action of heavy water (i. e., its ability to absorb ordinary water from or through the tissues much as absolute alcohol would do) and changes in osmotic pressure. These possible causes of physiological modification are in addition to direct toxic effect of deuterium compounds themselves. It is unknown whether or not a direct toxic effect exists.

In addition to these investigations with whole organisms some significant results have been obtained in experiments on the metabolism of special cells in the presence of water having a high deuterium content. Drs. Doan, Wiseman and associates in Ohio State's Department of Medical Research (58) have made a quantitative study of the influence of both 7% and 50%

heavy water on the metabolism of white blood corpuscles, by means of a Warburg apparatus. They find marked decreases in the rate of respiration in the presence of heavy water, with the effect much greater for the 50% heavy water, although no effect was produced either on the rate of CO_2 metabolism or on

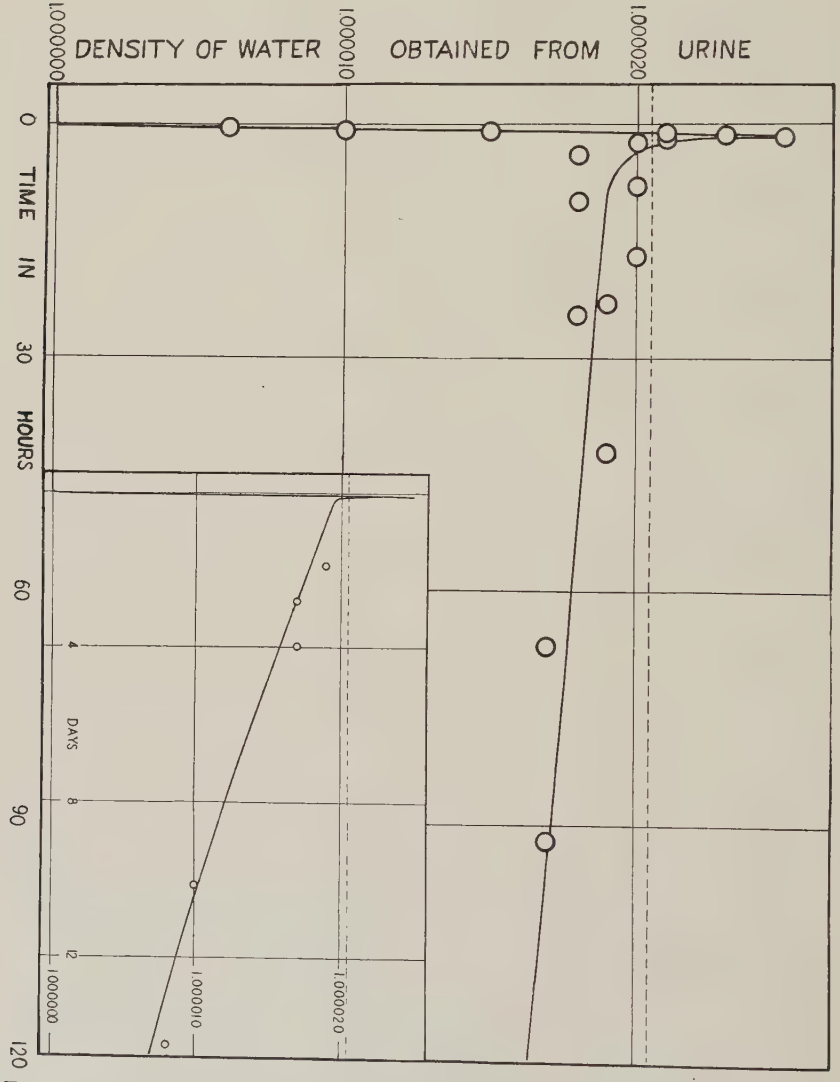


FIG. 14. Loss of Deuterium with urine following drinking of dilute heavy water. (Constructed from the data of Hevesy and Hofer.) The dotted line represents the specific gravity to be expected for water from a fluid produced by mixing two liters of 0.5% D_2O with 45 liters of ordinary water.

glycollosis. This result is interesting because natural causes which modify the respiration rate also modify CO_2 metabolism and glycollosis and the magnitudes of the several effects are usually related. Investigators at Princeton have also made extensive studies of the influence of D_2O on cell respiration and obtained smooth curves which relate the rate of respiration to the deuterium content of the water (59).

Pacsu (60) finds that the alcoholic fermentation of d-glucose in 95% heavy water proceeds nine times more slowly than in ordinary water, and in 60% heavy water with about two-thirds of the velocity in ordinary water. The fact that yeast which has first been cultured in 95% D_2O fails to regain activity when the culture solution is diluted to 45% D_2O shows that deuterium here exerts a permanent toxicity toward the zymase enzyme.

The tracer action of deuterium may be utilized in biological, as in chemical, research and it is probably safe to predict that this use in biological investigations opens a wider field for its utilization than the study of its direct physiological effects. An excellent example of this utilization is contained in the recent very interesting work of Hevesy and Hofer (61) who used deuterium to find how rapidly water taken internally becomes distributed through the human body. The experiment consisted in carrying out systematic deuterium analyses of the urine excreted by a person who drank two liters of water about 0.5% of whose hydrogen was deuterium. Figure 14 shows the results of the experiment. The ordinates measure the specific gravity of the water distilled from the urine. The abscissa represents the duration of the investigation. The two liters of 0.5% D_2O was taken at time zero. Analysis of the urine preliminary to the start of the investigation yielded normal water (cf. Fig. 2). The dotted line in the figure represents the specific gravity to be expected if the two liters of 0.5% heavy water were thoroughly mixed with the approximate 45 liters (two-thirds of body weight) of water present in the body. The figure shows that this distribution was attained in about three hours. One-half of the deuterium taken in the experiment was excreted in 10 days. Since this was excreted at the same rate as ordinary water in the body the conclusion can be drawn that one-half of the water contained in the human body (i. e., one-third of its weight) is replaced every 10 or 12 days. MacDougall and coworkers (62) found, in a similar experiment with rats, that one hour was sufficient to allow thorough mixing of the body water of the rat with water taken into the stomach.

By using foods or drugs in which ordinary hydrogen is replaced by deuterium so as to introduce the tracer it is obvious that deuterium may sometimes be used to obtain information on the nature and the rapidity of normal physiological processes.

CONCLUSION

References to many excellent pieces of research on or with deuterium have been necessarily omitted. The examples cited are sufficient to show the possibilities opened up by the use of deuterium as a tool of research and the wide range of research fields to which it is applicable. Research with deuterium requires, in the majority of cases, careful physical measurements of some type and ingenious utilization of the small differences which exist between isotopic species. Wider use of deuterium as a tracer, in various fields of research, appears to offer the greatest promise for more extended contributions to future research.

Deuterium is probably only a fore-runner of the use of other isotopes as research tools. The separation of oxygen isotopes has been partially accomplished and Polanyi and Szabo (63) have used the heavier isotope of oxygen as a tracer to determine the mechanism of ester hydrolysis. The complete or partial separation of other isotopes will probably soon be an accomplished fact. Developments of this character will not affect the simpler aspects of our chemistry. They will, however, equip us with yet more tools to attack the myriad problems of science.

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ARTIFICIAL RADIOACTIVITY

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University of California

INTRODUCTION

I am speaking tonight on a very new subject, for artificial radioactivity was unknown fourteen months ago. Indeed, some of the facts I shall speak about were brought to light within this very month. From the standpoint of physics, the developments within the year have gone forward with almost incredible rapidity, with results that have profoundly modified and enlarged our understanding of the atom.

HISTORICAL BACKGROUND

For a historical background, however, we must go back to 1896, the year of Roentgen's discovery of x-rays. At that time Professor Henri Becquerel investigated the possibility that this mysterious radiation might be given off spontaneously from natural substances. He had in mind particularly the class of substances that give off light of their own accord—phosphorescent substances. Becquerel had been studying the properties of phosphorescent substances and happened to have in his possession at that time some phosphorescent salts of uranium, which he had prepared fifteen years before. Almost immediately he discovered that uranium salts do give off a radiation like x-rays; for when the uranium salts were placed near a photographic plate enclosed in a light-tight box, after a period of time the photographic plate was activated.

Very soon Rutherford, then at McGill, showed that the radiations continuously emanating from uranium could be divided into two types: one called the alpha rays, which were very easily absorbed in matter and produced intense ionization, and a much more penetrating type called the beta rays. When a still more penetrating type of radiation was discovered, Villard named them the gamma rays. These names for the three types are still used, although now it is known that the alpha rays are the nuclei or centers of helium atoms, the beta rays are high-speed electrons, and the gamma rays are indeed very penetrating x-rays, which are of the same nature as light.

Soon other radioactive substances were discovered, and in 1898 Madame Curie isolated radium. At this stage a number of radioactive substances had been found. Some appeared to give off radiation continuously and constantly, while the radiation from others decreased with time.

This complicated mass of facts was reduced to order by the transformation theory of Rutherford and Soddy in 1903. According to this theory, the atoms of the radio-elements, unlike the atoms of the ordinary elements, are not stable, but undergo spontaneous disintegration, accompanied by the expulsion of an alpha or a beta particle. After the disintegration, the resulting atom has physical and chemical properties entirely different from the parent atom. It may in turn be unstable and pass through a succession of transformations, each of which is characterized by the emission of an alpha or beta particle.

These processes may be illustrated by considering the changes in radium, shown schematically in the first slide (Fig. 1). At any moment an atom of atomic mass 226 may become unstable and break up with explosive violence, expelling an alpha particle with a characteristic speed. Since the alpha particle is a helium atom of mass 4, the resulting atom is lighter than before and becomes an atom of a new substance, radon, of mass 222, which is an inert radioactive gas. This in turn breaks up, with the liberation of an alpha particle, and is converted into an atom of a nongaseous element, radium A. The next element in the series, radium B, emits a beta particle and thereby transforms into radium C, which is an element of very nearly the same weight and one unit up the periodic table.

For the purposes of the evening, this is all I need to say about the natural radioactive substances, the unstable atomic species existing at the present time in nature.

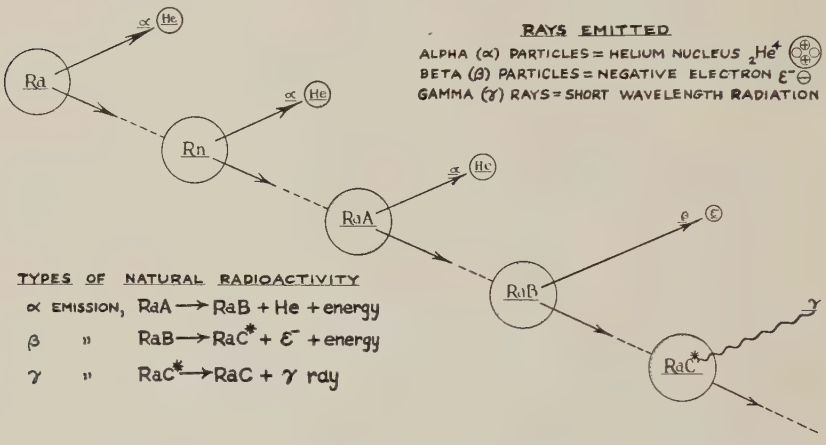
We now turn our attention to 1919, when Lord Rutherford for the first time transformed the ordinarily stable element nitrogen into oxygen. By this time Rutherford's theory of the atomic nucleus was well established. It was generally accepted that the nucleus, or center, of the atom contains more than 99.9 per cent of the atom's mass and energy and, moreover, that the nucleus possesses a positive charge that determines the number and configuration of the electrons outside the nucleus, and these extra-nuclear electrons determine the atom's

NATURAL RADIOACTIVITY

NATURAL SPONTANEOUS DISINTEGRATION

DISCOVERED IN URANIUM BY BECQUEREL (1896). RADIUM ISOLATED BY MME. CURIE (1898). RADIATIONS WITH DIFFERENT PENETRATING POWERS OBSERVED, CALLED α, β, AND γ RAYS. TRANSFORMATION THEORY ADVANCED BY RUTHERFORD AND SODDY (1903)—ATOMS OF RADIO-ELEMENTS ARE UNSTABLE AND UNDERGO SPONTANEOUS DISINTEGRATION.

EXAMPLE — SUCCESSION OF TRANSFORMATIONS (DECAY) OF RADIUM



· TRANSMUTATION ·

ARTIFICIALLY PRODUCED DISINTEGRATION

RUTHERFORD (1919) BOMBARDED NITROGEN WITH NATURAL ALPHA PARTICLES

reaction equation $_2He^4 + {}_7N^{14} \longrightarrow {}_8O^{17} + {}_1H^1 + \text{energy}$

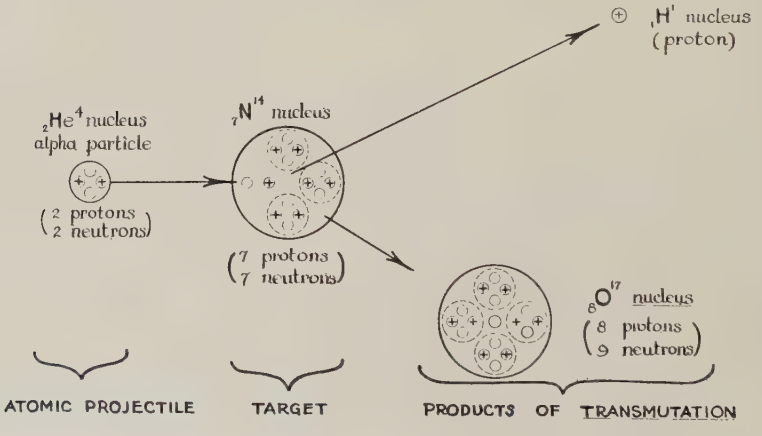


FIGURE 1—Upper. FIGURE 2—Lower.

place in the periodic table. Thus, on this theory, the age-old problem of alchemy, the conversion of one chemical element into another, was reduced to the definite problem of changing the amount of positive electricity in the atomic nucleus.

This Rutherford succeeded in doing by bombarding nitrogen with the alpha particles from radium. Several lines of evidence indicated that the constituent particles of the nucleus (then thought to be protons and electrons) were closely and tightly bound together, and that, therefore, disrupting the nucleus could be accomplished only by bombardment with atomic projectiles of very high energy, such as the alpha particles from radium. I should like to spend some time describing Rutherford's great experiments, for his works are classics in experimental physics, but time permits me only to state the established experimental results. He showed that when an alpha particle or helium nucleus, traveling at high speed, hits the nucleus of a nitrogen atom, occasionally the alpha particle sticks, and at the same time a proton, or hydrogen nucleus, is thrown off with a great deal of kinetic energy. Thus is formed O^{17}, a heavy form of oxygen which was not known in nature at that time but since has been discovered as a normal constituent of chemical oxygen by Giauque and Johnston—and by the way, the latter gentleman is Professor Johnston of your department of chemistry.

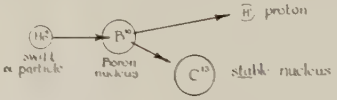
This classic nuclear reaction is shown in the next slide (Fig. 2). For most purposes, an atomic nucleus is sufficiently specified by giving the atomic number, which is the positive charge on the nucleus in integral multiples of the proton charge, that determines its place in the table of elements—what element it is—and the mass number, in multiples of the proton as well. Actually, in fact, atomic nuclei do not have masses that are exact multiples of that of the proton, but that need not worry us here. Thus the upper right-hand corner of the symbol of the element is reserved for the isotopic mass, and the lower left-hand corner for the atomic number, and the nuclear reaction of Rutherford is written as shown in the slide. The double charge on the helium nucleus is added to the seven-fold charge of the nitrogen, and the single charge of the hydrogen is subtracted, resulting in a net increase of one positive charge, thereby forming oxygen. Likewise, the net increase in weight is 3 units, making O^{17}.

· ARTIFICIAL · RADIOACTIVITY ·
INDUCED BY NATURAL ATOMIC PROJECTILES

WHEN BORON IS BOMBARDED BY NATURAL ALPHA PARTICLES —

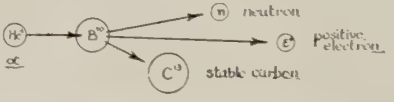
I. RUTHERFORD AND CHADWICK SHOWED (1924) THAT ENERGETIC PROTONS ARE EMITTED IN THE PROCESS

- A TRANSMUTATION $_2He^4 + {}_5B^{10} \longrightarrow {}_6C^{13} + {}_1H^1 + \text{energy}$



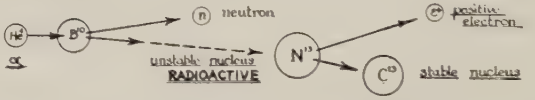
II. CURIE-JOLIOT OBSERVED (1933) THAT NEUTRONS AND POSITRONS ARE ALSO EMITTED.

IT WAS POSTULATED — $_2He^4 + {}_5B^{10} \longrightarrow {}_6C^{13} + {}_0n^1 + \varepsilon^+ + \text{energy}$



III. HOWEVER, CURIE-JOLIOT FOUND (1934) THAT THE POSITRON EMISSION PERSISTS AFTER CESSATION OF THE BOMBARDMENT. ATTRIBUTED TO THE RADIOACTIVITY OF A PRODUCT

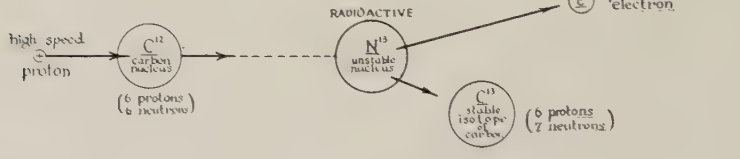
$_2He^4 + {}_5B^{10} \longrightarrow {}_7N^{13} + {}_0n^1$ then $_7N^{13} \longrightarrow {}_6C^{13} + \varepsilon^+ + \text{energy}$



ARTIFICIAL RADIOACTIVITY
INDUCED BY ATOMIC PROJECTILES ACCELERATED IN THE LABORATORY

I RADIOACTIVE NITROGEN IS FORMED BY BOMBARDMENT OF CARBON WITH PROTONS

$$_1H^1 + {}_6C^{12} \longrightarrow {}_7N^{13} \qquad {}_7N^{13} \longrightarrow {}_6C^{13} + \varepsilon^+ + \text{energy}$$



II DEUTERON BOMBARDMENT OF CARBON ALSO PRODUCES RADIO-NITROGEN

$$_1H^2 + {}_6C^{12} \longrightarrow {}_7N^{13} + {}_0n^1 + \text{energy}$$

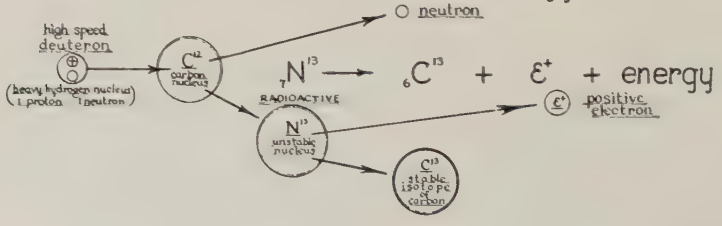


FIGURE 3—Upper. FIGURE 4—Lower.

Following the first definite example of the artificial transmutation of the elements, many other transmutations were carried out. Most of the lighter elements up to potassium were transformed, one into another, by alpha particle bombardment, in each case with the emission of a proton.

The next episode in our historical background brings us up to 1932, when Irene Curie, the daughter of Madame Curie, and her husband, F. Joliot, discovered that boron gives off positrons, the positive electrons discovered that same year by Professor Carl Anderson of the California Institute of Technology, and neutrons, the neutral particles of protonic mass discovered by Chadwick only a few months earlier. They concluded that the reactions depicted on the next slide (Fig. 3) occurred. When boron is disintegrated by alpha particle bombardment, alternative reactions may occur: either a proton may be emitted, as observed by Rutherford and Chadwick, or a neutron and positive electron together—as though a proton is not itself a simple particle but is made of a neutron and positive electron, and that sometimes the process of expulsion of the proton in the reaction is so violent that the proton itself is broken up into its constituent parts.

THE DISCOVERY OF ARTIFICIAL RADIOACTIVITY

The next episode is the birth of artificial radioactivity. One day, more than six months after they had first noticed the emission of positrons from boron bombarded by alpha particles, Curie and Joliot observed (accidentally, I believe) that the positron emission continued on after the alpha particle bombardment had been stopped—they happened to remove the radium from the vicinity of the boron. With this observation, they had discovered that a new kind of radioactivity is stimulated in boron by alpha particle bombardment. This discovery made it evident that the neutron and positron do not come off simultaneously when boron is bombarded by the alpha particle, but that the neutron in the reaction is emitted first, leaving a nucleus having a charge of 7 (hence, the nitrogen nucleus) and a weight of 13, which is lighter than ordinary nitrogen and presumably, therefore, unstable. They proved chemically that the radioactive substance formed is, in fact, an isotope of nitrogen, and christened it "radio-nitrogen." As shown in the slide, the positron emission converts the radio-nitrogen into C^{13}.

In those pioneer experiments they produced two other new radioactive substances—radio-magnesium and radio–silicon—and since that time other radio-substances from alpha particle bombardment have been discovered by various investigators.

In their first discussion of their important discovery, Curie and Joliot suggested that such radioactive substances might well be produced by bombardment with other atomic projectiles, especially protons, deuterons, and neutrons. This suggestion seemed to be almost a certainty to us in Berkeley. Since, for more than a year, we had been studying the disintegration of various elements under deuteron bombardment, and had observed the almost universal emission of protons and neutrons from bombarded targets, it appeared most plausible that the neutrons we had been observing so universally were involved in the alternative nuclear reaction in which artificial radioactive substances were formed.

In particular, it seemed likely that radio-nitrogen could be formed by a deuteron entering a C^{12} nucleus, forming N^{13}, with the emission of a neutron, or by the direct addition of a proton to the C^{12} nucleus, as shown in the next slide (Fig. 4). My colleagues, Dr. M. C. Henderson and Dr. M. S. Livingston, and I investigated this interesting possibility, and immediately we found that radio-nitrogen is formed, indeed, in both of these ways. In those first experiments we also bombarded various other substances with high-speed deuterons, and found, to our surprise and joy, evidence of the production of many new radioactive substances in addition to radio-nitrogen. At about the same time several other laboratories in the world, notably Cambridge, Washington, and Pasadena, more or less independently carried on investigations establishing that radioactive substances can be produced in this way.

In the intervening months, intensive work in the various laboratories has gone forward, with the result that a great many new radioactive substances have been produced, identified, and studied more or less extensively. Also, following the discovery of Professor Fermi, many new radioactive substances produced by neutron bombardments have been studied. Although the discovery of artificial radioactivity is hardly more than a year old, the facts that have been brought to light are already so extensive that I could hardly hope to give an adequate summary this evening. It therefore would seem desirable that I confine my attention for the remainder of the

time to some of the results of recent investigations carried on by my colleagues and myself in California.

EXPERIMENTAL METHODS

But before discussing experimental results, it is desirable to say something about experimental methods for accelerating protons and deuterons to high speeds. There is a natural tendency to relegate to the background the experimental methods and techniques and to regard the results brought to light in nuclear investigations as of first importance. It is so easy to forget that the nuclear investigations are made possible by the development of experimental methods and techniques. How greatly was nuclear physics enriched by the cloud chamber of C. T. R. Wilson!

Methods for the acceleration of charged particles can conveniently be classified into three types: First, the high-voltage method, in which the ions fall through a requisite difference of potential in a vacuum tube. The second method might be called the surf-board method, because the ions are caused to travel along in the field of a traveling wave. The third class of methods of accelerating ions might be termed "resonance methods," or methods of multiple acceleration.

The high-voltage method is, in a sense, the most straightforward, and has much to commend it and is widely used. In the classic experiments of Cockcroft and Walton, in which, for the first time, transmutations were accomplished by bombardment with accelerated ions, a vacuum tube capable of withstanding about 800,000 volts was used. Lauritsen and his collaborators in Pasadena have accomplished a great deal with a vacuum tube, across which is applied about a million volts supplied by the high-voltage transformers in the high-tension laboratory of the California Institute of Technology. Using a Van de Graaff generator, Tuve, Hafstad, and Dahl, in Washington, have been able to accelerate ions at voltages as high as 1.2 million. This high voltage was distributed along a long vaccum tube very nicely, by means of a series of electrodes maintained at proper differences of potential by the corona along the tube. Van de Graaff and his collaborators at Round Hill, Massachusetts, are constructing a similar type of tube in which the voltage is distributed between the electrodes by a series of resistances. The tube is ultimately intended to withstand the full voltage available from their gigantic electrostatic generator, which is more than five million.

Professor J. W. Beams, at the University of Virginia, during the past year or two has been engaged in the development of the surf-board method, and already has made such progress that it appears that the method will be very useful for producing small currents at very high voltage. Beams has already succeeded in accelerating protons to voltages above two million, and it appears not improbable that he will be able to reach double this voltage in this way. The inherent features of the method are such as to restrict it to the production of small current in pulses, a restriction which, however, makes it almost ideally adapted to cloud chamber experiments.

The methods of multiple acceleration by resonance with an oscillating electric field have the advantage that they do not require high voltages. The general resonance principle is familiar even to the layman. A child in a swing knows that a high swinging velocity can be achieved by one big push, corresponding to the single acceleration of an ion by application of high voltage, or by a succession of small pushes properly timed with the swinging motion, corresponding to the resonance acceleration of ions. One type of apparatus that uses this resonance principle involves both a magnetic field and an oscillating electric field. We have in our laboratory two of this sort. The larger one of the two, which has been used in the nuclear investigations that I shall speak about, is shown on the next slide (Fig. 5). The most prominent feature of the apparatus is the giant electro-magnet, weighing something like 85 tons. Thus far we have accelerated deuterons to energies only slightly above five million, and the most energetic deuterons we have actually used in nuclear investigations had energies of about 4.5 million volts. The time, of course, will come when we will want to go up to higher voltages, and from our recent experience we are confident that, by using the full power of the magnet, we will be able to produce deuterons of energies above ten million volts, and possibly above fifteen million volts.

The ions are accelerated in the vacuum chamber between the poles of the magnet. The function of the magnetic field is to cause the ions to travel with constant angular velocity most of the time in circular paths. Within the chamber there are two semicircular hollow electrodes, between which is applied a high frequency potential difference. The ions circulate

FIGURE 5

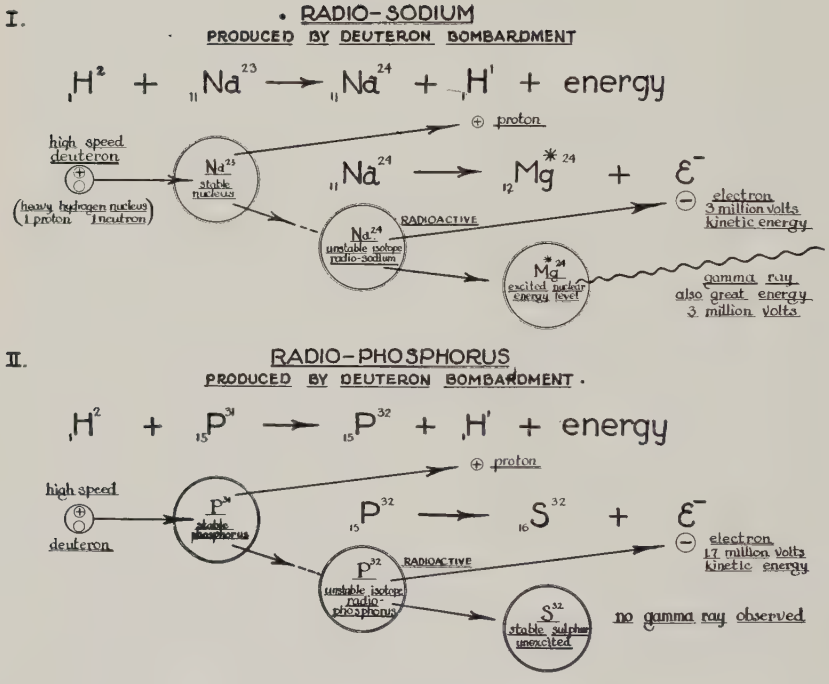

I.
RADIO-SODIUM
PRODUCED BY DEUTERON BOMBARDMENT
$_1H^2 + {}_{11}Na^{23} \rightarrow {}_{11}Na^{24} + {}_1H^1 + \text{energy}$
high speed deuteron
(heavy hydrogen nucleus 1 proton 1 neutron)
stable nucleus
proton
$_{11}Na^{24} \rightarrow {}_{12}Mg^{*24} + \varepsilon^-$
electron 3 million volts kinetic energy
RADIOACTIVE
unstable isotope radio-sodium
excited nuclear energy level
gamma ray also great energy 3 million volts
II.
RADIO-PHOSPHORUS
PRODUCED BY DEUTERON BOMBARDMENT.
$_1H^2 + {}_{15}P^{31} \rightarrow {}_{15}P^{32} + {}_1H^1 + \text{energy}$
high speed deuteron
stable phosphorus
proton
$_{15}P^{32} \rightarrow {}_{16}S^{32} + \varepsilon^-$
electron 1.7 million volts kinetic energy
RADIOACTIVE
unstable isotope radio-phosphorus
stable sulphur unexcited
no gamma ray observed

FIGURE 6

around from within one electrode to within another, and as they cross the diametrical region they gain increments of kinetic energy corresponding to the potential difference. Inasmuch as the angular velocity of the ions is determined by the magnetic field alone, they can be made to spiral around in synchronism with the oscillating electric field, with the result that they can be made to gain successive increments of velocity, and hence, going faster and faster on ever widening spirals, finally they emerge at the periphery of the apparatus where they are withdrawn by a deflecting electrostatic field through a thin aluminum window to the outside world. The swiftly moving deuterons travel a distance of about 17 cm before being stopped by their loss of energy in passing through air. The beam is visible as a bright blue glow; for the beam passing through the air excites the atoms and molecules to the emission of visible light. Experiments on the radioactivity induced by deuteron bombardment are carried out simply by placing the substance to be bombarded in the path of the deuteron beam just outside the aluminum window for any desired period of time, and then, taking the bombarded target away to an ionization chamber or a Wilson cloud expansion chamber, or any other apparatus used for studying the radiation given off from the activated target.

THE NEUTRON-CAPTURE REACTION

I have already remarked that in our first experiment, in which we bombarded various substances with deuterons, there was evidence of the formation of several new radioactive substances. In some cases, radioactive nuclei are formed in nuclear reactions, in which neutrons or alpha particles are emitted. But in the majority of cases it is found that the neutron of the deuteron is captured and the proton is emitted with high speed. This general type of reaction, which, for convenience, is called the neutron-capture reaction, has been observed to occur for many of the elements, and is conveniently illustrated by the cases of radio-sodium and radio-phosphorus shown in the next slide (Fig. 6).

Thus Na^{23}, upon being bombarded by the deuterons, acquires the neutron of the deuteron and becomes heavier by the weight of the neutron, that is Na^{24}. Na^{24} does not occur in nature and is energetically unstable, and in the course of 15½ hours, on the average, the radio-sodium atom emits a high-speed electron

(i. e., a beta particle) from its nucleus, becoming Mg^{24}. The newly created magnesium nucleus is formed with an excess of energy, which it immediately radiates as a very energetic gamma ray of energy above three million volts. The beta and gamma rays emitted from radio-sodium are thus more powerful than the radiations from radium. Indeed the gamma rays are more powerful than those from any of the known natural radioactive substances.

In a like manner, radio-phosphorus is formed. Radio-phosphorus is interesting in two respects. In the first place, it has the longest average lifetime of any of the artificial radioactive substances thus far studied. Its half-life is about 15 days. The other interesting feature of radio-phosphorus is that it does not emit any gamma rays. A pure beta ray spectrum is observed. It appears that the S^{32} nucleus, that results when P^{32} emits a beta particle, is formed in its normal state without an excess of energy to be radiated.

THE TRANSMUTATION FUNCTION FOR THE NEUTRON-CAPTURE REACTION

Perhaps the most interesting result of all was the mere fact that we were able to transform elements of as high atomic number as sodium and phosphorus by bombardment with deuterons of less than two million volts of energy. It was quite incomprehensible that deuterons of such low energy were able to overcome the high repulsive forces of the positive charges on these nuclei, for it was presumably well known that these repulsive forces produce an effective barrier around the nuclei corresponding to several million volts.

Prior to the advent of the wave mechanics, it was thought that a charged particle bombarding a nuclear potential barrier does not penetrate into the nucleus unless it has enough energy to climb the nuclear wall and enter over the top, and so, in accordance with classical ideas, one would not expect sodium to be transformed by bombardment with two million volt deuterons. But Gurney and Condon, and Gamow, independently applied the wave mechanics to nuclear problems and made it clear that charged particles penetrate right through nuclear potential barriers. Indeed it was the existence of this tunnel effect that encouraged Cockcroft and Walton to try to disintegrate lithium by bombardment with protons of less than a million volts energy, with the result that is now so well known.

But even the Gamow theory did not make plaúsible the observation of the transformation of sodium by one and one-half million volt deuterons. The apparent incompatibility of the experiments with current theory was enhanced by the further observation that copper could be rendered radioactive by bombardment with deuterons of slightly more than two million volt energies.[1] Thus it was of much interest to my colleagues, Drs. R. L. Thornton and E. M. McMillan, and myself, to investigate the variation of the nuclear reaction with the energy of the bombarding deuterons in the several cases, which we did as follows:

In order to obtain an energy-yield curve for a reaction giving a radioactive product, one measures the intensity of activation of a number of samples exposed to bombardment by particles of different energies. The relative bombarding current and exposure time must be accurately known for each sample, a requirement which is most easily and satisfactorily met by activating them simultaneously. This was done by using as a target a stack of thin foils of the substance being investigated, through which the activating deuteron beam was sent. The energy of the deuterons traversing any particular foil is then determined by their initial energy, and the stopping power of the preceding foil and the measured activities give directly the differential excitation curve. Thus, for example, a stack of 15 aluminum foils, each having a stopping power of about 8 mm. air equivalent, was placed in the beam of the deuterons emerging from the aluminum window of the magnetic resonance accelerator, and, after exposure to the beam for a few minutes, was removed, and the radioactivity induced in each foil was observed by placing the individual foils in the ionization chamber of an electroscope.

The variation of the probability of activation of an aluminum nucleus with the energy of a bombarding deuteron (sometimes called the differential excitation function, or thin target transmutation function) thus observed, is shown in the next slide (Fig. 7). I am showing the aluminum results first because it it believed in this case the observations were most

[1]Recently we have made preliminary observations that indicate that radiomolybdenum is formed by bombardment of molybdenum with 3.5 million volt deuterons, and that possible gold is rendered radioactive by bombardment with 4.5 million volt deuterons. However, further work must be carried out before it can be concluded with confidence that these deuteron reactions actually occur, as there are yet possibilities of contaminations.

precise. For similar observations on radio-sodium and radio-silicon, thin mica foil was used, as mica contains both silicon and sodium. Since the half-life of radio-silicon is 2.8 hours, and that of radio-sodium is about 15.5 hours, the two radio-activities were readily distinguished in the mica foil, the silicon activity being predominant in the first few hours after deuteron bombardment, and the sodium activity persisting for days afterwards. The results in these two cases are shown in the next two slides (Figs. 8 and 9). The observations with copper foils are shown in the last slide (Fig. 10).

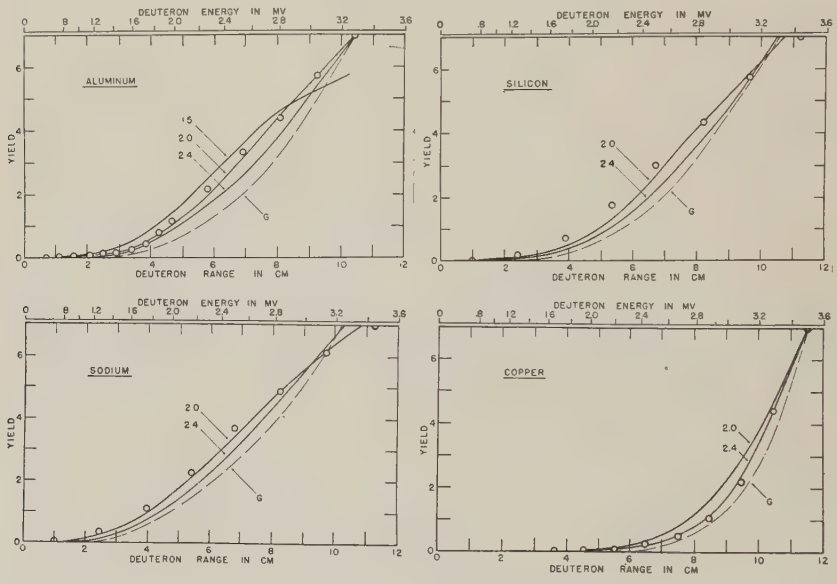


FIGURE 7—Upper left.
FIGURE 8—Upper right.
FIGURE 9—Lower left.
FIGURE 10—Lower right.

It is evident that the excitation curves in the four cases are of similar form. The yield of radioactive substance for a thin target, plotted against the range of the bombarding deuteron, instead of its energy, rises approximately linearly with the range (with a "tail" at the beginning). The experimental results clearly indicated a new general kind of excitation function for this class of nuclear reactions.

THE OPPEMHEIMER-PHILLIPS THEORY

We were all curious to know something about the fundamental physics underlying this new type of transmutation

function, and Professor J. R. Oppenheimer and Dr. Melba Phillips soon came forward with a theory that explained everything in most gratifying fashion. The essence of their theoretical explanation lies in the fact that reactions of the type here concerned can occur without requiring the penetration of a charged particle through the nuclear coulomb potential barrier which opposes the entry of the deuteron. The mechanism postulated can be described in the following way: Consider the deuteron as built of a proton and neutron with the binding energy I. Because of the wave nature of the particles, this structure is not confined within a sharply limited volume, but there is a finite chance that the neutron or proton may be found some distance away from the center of mass. This chance decreases rapidly with the distance. When the deuteron is projected against the nucleus, the proton is held back by the coulomb field. This distorts the probability distribution of the proton in such a way that, for a given distance of the deuteron center of mass from the nucleus, the chance of finding it in the center of the nucleus is very much reduced. On the other hand, the neutron is immune to the action of the electrostatic field, and its probability distribution can overlap the center of the nucleus; this distribution is, in fact, distorted by the forces involved in the deceleration of the neutron in such a way as to increase its density on the side toward the nucleus. Therefore the neutron has a relatively larger chance of being within the nucleus, and while there, of undergoing a reaction in which it becomes bound, forming a new nucleus. The extension of the neutron distribution varies with I, becoming greater as I decreases. It is the relatively small value of I (about 2 million volts) that causes the slow energy variation of this type of reaction by flattening out the neutron probability distribution.

The actual shape of the curves giving the variation of the neutron-penetration with energy depends on the value of I. Since this most probably lies between 2 and 2.4 million volts, as indicated by other experimental evidence, the curves for these two cases have been compared with the experimental values. They are plotted as solid lines, as shown in the several slides. The ordinates of the theoretical curves are adjusted to make them fit at the highest experimental point, except in the cases of sodium and silicon, where the measured values of these are almost certainly too low because of recoil effects.

The Gamow function is also plotted on the figures as dotted lines for comparison. It is seen that the results are in gross disagreement with the Gamow theory, but on the other hand, the results of Oppenheimer and Phillips show a very satisfactory agreement with the observed values. Consider the first case of aluminum, which is the most trustworthy experimentally. With pure aluminum foils the activity if very large compared to that of any possible contamination. There is no error in the highest point caused by recoil. It is seen that the Oppenheimer-Phillips function with I = 2.0 fits extremely well, while with I = 1.5 and I = 2.4 it is off by more than the experimental error.

The fit for sodium and silicon is also best for I = 2.0. Here the possibility of experimental error is somewhat greater, and the apparent deviation in the case of silicon between 1.5 and 2.5 million volts may not be real. The results for these two elements are of chief interest in showing that this type of excitation curve is not a characteristic of any particular reaction, but of a class of reactions. The comparative values for sodium and silicon show also that the steepness of the curve increases with atomic number, as it should.

For copper the fit seems to be best with I = 2.4. Here, because the greatest variation of the function occurs in a narrower voltage range, the different theoretical curves are not as widely separated as in the other cases, and the apparent better agreement with I = 2.4 may not be real.

Thus the theory of Oppenheimer and Phillips, which was developed from such attractively simple and reasonable assumptions, is adequate to explain the observed excitation curves. The agreement of the experiment with the theory is so satisfactory in detail that the results yield a completely independent measure of the binding energy of the deuteron, and this result itself is of much importance.

Moreover, acceptance of the Oppenheimer-Phillips theory as correct leads to another very important conclusion. Just as the variation of the transmutation yield with energy for a given atomic number is slower than expected on the Gamow theory, likewise the variation with atomic number for a given energy is much slower. This has the consequence that it will be possible, with the available deuteron energies, to produce nuclear reactions much farther up the periodic table than one could have hoped for before.

UTILITY OF ARTIFICIAL RADIOACTIVITY

Before closing it is well to remark that, now that radioactive forms of many of the elements can be manufactured in the laboratory, many new avenues of research are opened up. It is reasonable to expect that artificial radioactive substances will play a possibly more important role in the physical and biological sciences in the not distant future than the natural radioactive substances have in the past. Certainly extensive study of the artificial radioactive substances will lead to a greatly enlarged understanding of atomic structure. But, more particularly, these new radioactive substances provide many and varied ideal sources of beta and gamma rays. For example, radio-phosphorus provides beta radiation, free from gamma rays, that can be used conveniently for studies of the behavior of high-speed electrons in matter. Also some of the new radioactive substances give off gamma rays that are far more energetic and penetrating than any from the natural radioactive substances, and the use of these gamma ray sources undoubtedly will lead to important advances in our knowledge of the interaction of radiation and matter.

There may result also many important biological applications. I hesitate to express views in this direction, but some of my medical colleagues think it quite possible that the discovery of artificial radioactivity will ultimately be of great importance to medicine. Opinions of this sort, of course, are highly speculative, and I leave it to you to estimate the advantages for radiation therapy and biological research, of radioactive substances having practically any desired chemical and physical properties.

In conclusion, may I say that, while I have not given you a comprehensive survey of this new world of knowledge and investigation, I do hope that I have given enough of an account of things that have interested us in California in recent months, to make it clear that there is a new science—shall we call it nuclear physics or shall we call it nuclear chemistry?

NUCLEAR TRANSFORMATIONS AND THE ORIGIN OF THE CHEMICAL ELEMENTS

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Until the beginning of this century the chemical elements have been considered as certain prime substances, and corresponding atoms as elementary constituent parts from which more complex molecules can be built up. The discovery of radioactive phenomena and their interpretation, due to Rutherford, as the spontaneous disintegration of atomic nuclei has shown, however, that chemical elements can be, under certain circumstances, transformed into one another and such transformations occur spontaneously for the heaviest of the known elements. Rutherford succeeded also, as early as 1919, in producing artificial transformations of light, usually stable, atoms, bombarding them with the intensive beams of fast α-particles. The first element which was disintegrated in such a way was nitrogen, which in the collision with an α-particle emits a proton and is transformed into a heavier isotope of oxygen. The corresponding nuclear reaction can be written in the form:

$$ {}_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1H^1. \qquad (1) $$

Further investigations of Rutherford and his school have shown that analogous processes can happen for the most of the light elements and that the probability of disintegration decreases very rapidly with increasing atomic number so that already for $Z > 20$ no emission of protons can be observed. It was also found that the probability of disintegration increases very rapidly with increasing energy of the bombarding α-particles. Both observations can be satisfactorily explained by the theory of artificial nuclear disintegrations worked out by Gamow according to which the probability of such transformations depends on the transparency of the potential barrier surrounding each nucleus and preventing the incident α-particles from entering the nuclear structure. The theoretical expression for the transparency of such barriers for incident α-particles can be worked out on the basis of modern wave-mechanics

and is in very good agreement with the detailed results of experiments (*1*).

Gamow concluded from this theory that the transparency of nuclear barriers must be much larger if the bombarding particles are protons. Due to the smaller charge and mass of a proton, the probability of penetration of a proton into a given nucleus is the same as for an α-particle with 16 times larger energy. Remembering that nuclear transformations have been observed by Rutherford only for α-particles with the energies of several million electron-volts, one could conclude that in the case of proton-bombardment one can expect observable results already for energies of a few hundred kilovolts. These considerations encouraged Cockcroft to construct special high-voltage apparatus in which he could produce the beams of protons with the energies up to 500 kilovolts for the use of nuclear bombardment. Bombarding with these protons a target of lithium he was able to observe the expected nuclear transformation at voltages as low as 250 kilovolts (*2*). In this case the proton penetrates into the nucleus of the lithium atom and breaks it up into two α-particles. The reaction can be written in the form:

$$ {}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4, \qquad (2) $$

with the liberation of a large amount (about 18 x 10^6 e. v.) of energy. Bombarding by his proton-beams different light elements, Cockcroft was able to find other examples of the reactions of the same type and to prove the validity of the theoretical formula for the probability of artificial disintegration. At the present time various ingenious apparatuses producing fast beams of particles have been developed in different laboratories throughout the world, increasing our knowledge concerning different types of artificial transformations of light elements. It has been mentioned above that due to the decreasing transparency of nuclear potential barriers the reactions of such type can be observed by present voltages only in the region of light elements and one requires proton-beams of about 10 x 10^6 e. v. in order to penetrate into the nuclei of such heavy elements as mercury and lead.

Quite a new type of nuclear reactions was recently discovered by Fermi (*3*), who was able to show that the nuclei of different, especially heavy, elements bombarded by neutrons can be transformed into their heavier isotopes. Such "capture" phenomena can only be explained as the sticking of incident

neutrons to the bombarded nucleus with the liberation of surplus energy in the form of γ-radiation. It was observed by Fermi that the probability of such radiative capture of neutrons increases with their decreasing energy and that one can observe the maximum effect for those neutrons slowed down by collisions with other nuclei to their ordinary thermal velocities. One can easily understand that such type of nuclear reaction can happen without difficulty also for heavy nuclei since, due to the absence of repulsive forces between the neutron and the nucleus, there is no potential barrier preventing the penetration of the neutron into the nuclear structure. The theory of radiative capture of slow neutrons by heavy nuclei was worked out by Bethe and is in satisfactory agreement with the experimental evidence. The heavier isotope formed as the result of the capture of a neutron by certain nuclei can be unstable and subject to the spontaneous emission of an electron which leads to the formation of a nucleus with larger charge and larger mass than the original one. Thus the radiative capture of neutrons and consequential β-disintegration leads step by step to the formation of more complex nuclei. As the typical Fermi-reaction one can write down the process of radiative capture of a neutron by the nucleus of ${}_{53}I^{127}$:

$$\left.\begin{aligned} {}_{53}I^{127} + {}_{0}n^{1} &\rightarrow {}_{53}I^{128} + h\nu \\ {}_{53}I^{128} &\rightarrow {}_{54}Xe^{128} + \bar{\beta} \end{aligned}\right\} \tag{3}$$

leading to the nucleus of ${}_{54}Xe^{128}$.

Turning our attention from the experimental evidence obtained in the laboratories to the processes happening in the universe, we may at once conclude that there is not much chance for the nuclear reactions to occur around us on the earth. In fact the probability of nuclear transformation by the velocities corresponding to ordinary temperatures is extremely small and need not be taken into account. Only neutrons can produce nuclear transformations at small velocities, but all neutrons are already hidden inside of different stable nuclei and in order to get them out one must use very fast beams of protons or α-particles. If, however, we consider the processes happening inside of stars, in the hottest places of the universe, the situation might be rather different; in fact, the thermal velocities corresponding to several million degrees centigrade are already sufficient to produce artificial trans-

formations of the lightest elements. Using Gamow's formula for the probability of nuclear transformations by collision, Atkinson and Houtermans (*4*) calculated the chance for a proton, moving with thermal velocity, to penetrate into the nuclei of different elements and estimated the periods of time necessary for 50% transformation of different substances mixed up with hydrogen under the conditions governing inside of our sun (density ~ 1; temperature $\sim 60 \times 10^6$ °C.). They obtained the following numbers: for *Li*, 34 min.; for *B*, 14 years; for *Ne*, 1×10^9 years; and for *Pb*, 10^{61} years (!), which shows that only the lightest elements are easily transformed by proton-bombardment under the conditions governing in the interior of stars. Making the same calculations for collisions with helium-nuclei (α-particles) one obtains very small probabilities even for the lightest elements so that such processes are very improbable even at intrastellar temperatures; still smaller probabilities are obtained for the disintegrative collisions with heavier particles. Thus the thermal nuclear transformations in stars are of importance only for the lightest elements and are entirely due to the collisions with hydrogen atoms which are always present in large amount in stellar substance.

The discovery of the radiative capture of neutrons by heavy nuclei opens, however, new possibilities for the intrastellar nuclear reactions. The neutrons which can be ejected from the nuclei of light elements by collisions with protons may stick to the nuclei of different heavy elements thus securing the possibility of the formation of still heavier nuclei. It might be that this effect plays a very important role in the formation of different elements in the interior of stars.

We come now to one of the most interesting questions concerning the physical state of the matter deep inside of stars. It is of course clear that due to extremely high temperatures and pressures in these regions all molecules are dissociated into separate atoms and even more all atoms are completely ionized, all electronic shells being torn away from the nuclei by the violent collisions. We may consider the substance inside of a star as the mixture of bare nuclei and free electrons, a mixture which can be treated as the ordinary mixture of two ideal gases: nuclear gas and electronic gas. Now, due to the fact that the average number of electrons in the atom is about fifty per nucleus, the partial pressure of electronic gas will, according to Dalton's law, form about 98% of the total pressure and is the only one which must be taken into account.

The equilibrium problem between the pressure of the electronic gas in the star's interior and the gravitational pressure of the outside layers of the star was considered by Landau (*5*) and we give here a short account of his calculations. The pressure of an ideal gas containing N particles in the cube with the side l is, as is well known, given by:

$$P = \frac{1}{6} \cdot \frac{N}{l^2} \cdot n \cdot p = \frac{1}{6} \cdot \frac{N}{l^2} \cdot \frac{v}{l} \cdot mv, \tag{4}$$

where v is the velocity of particles, $n = \frac{v}{l}$ the number of collisions of a single particle with the wall per second and p the momentum equal to mv in the nonrelativistic case. For the ordinary isothermic compression $v = const.$ and the pressure P is inversely proportional to l^3; i. e., directly proportional to the density $\rho = \frac{N}{l^3}$. (Boyle-Mariotte law).

If, however, l becomes very small, the motion of different particles of our electronic gas must be quantised and no more than two electrons may stay on the same energy level (Pauli principle). With still decreasing l (increasing density), the distances between quantum levels become larger so that finally all levels will be densely occupied by electrons (this state is called saturated Fermi-gas), and the further compression must be inevitably connected with the increase of the velocity v. According to the fundamental relation of quantum theory, the momentum of the particle moving in the space of linear dimension l is given by:

$$p \sim \frac{h}{l},$$

where h is the quantum-constant; thus for saturated gas the momentum is inversely proportional to l. As far as the momentum is small compared with mc (velocity v small compared with the velocity of light), we can use the relation $v = \frac{p}{m}$, which means that the velocity itself is inversely proportional to l. The formula (4) shows us that in this region of densities the pressure P is inversely proportional to l^5; i. e., directly proportional to $\rho^{5/3}$. For still larger densities the average velocity

of the particles approaches the velocity of light. After this limit we must write $n = \frac{c}{l}$ for the number of collisions and still use the formula (5) which is correct also in the relativistic case (the increase of p is here due to the increase of the mass

$$\left(m = \frac{Mo}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \right)$$

We see that for such large densities the pressure P varies as $\frac{1}{l^4}$ or as $\rho^{4/3}$. The diagrammatic representation of the (p, ρ)-relation for the ideal electronic gas is shown on Fig. 1, by the curve I.

The outside pressure P' due to gravitation is, as is well known, proportional to $\rho^{4/3}$ and the coefficient of proportionality depends on the total mass M of the star. The curves II′, II″ and II‴ represent (P′, ρ)-curves for three different masses. We see that if M is small (curve II′) the inside pressure will be always larger and the star will expand and cool down until it will be turned into a large piece of stone. For somewhat larger mass (curve II″) there is a state of stable equilibrium between P and P' and the finite stage of the star will have inside a region filled up with nonrelativistic saturated Fermi-gas. For still larger masses (curve II‴) the inside pressure will never be able to oppose the weight of stellar substance and the star would collapse into a mathematical point (!) unless the further compression would be stopped by intranuclear repulsive forces between the particles of nuclear gas. This will happen when the distance between the particles is of the order 10^{-12} cm.; i. e., when the density approaches the value of 10^{12} relative to water! Thus we come to the conclusion that such a star will have in its center a very dense nucleus differing from the atomic nuclei only by its size which can be several miles in cross section. By calculations still further elaborated Landau was able to show that the limiting mass for which the stellar nucleus must be formed is about one third of the mass of our sun. Consulting astronomical data we find that this corresponds to the lower limit of stellar masses, which means that *all stars possess such nuclei which evidently represent the sources*

of the stellar energy radiated in such large amounts into interstellar space.

The question of the mechanism of energy-liberation is not yet quite clear but one can easily see that the gravitational energy alone liberated in the compression (Helmholtz's old theory) to such large densities would be enough to secure sufficiently long periods for stellar lives.

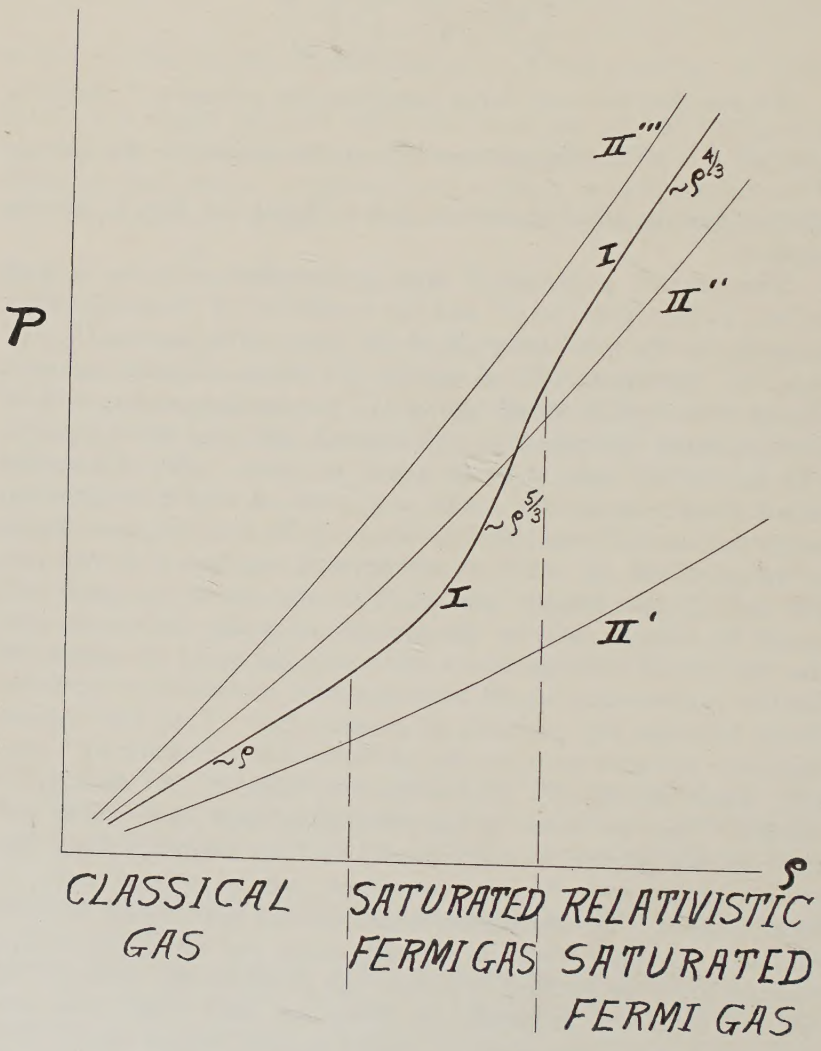

FIGURE 1

In this article we are interested especially in the role played by stellar nuclei in the formation of heavy elements. One can easily imagine that the stellar nucleus may not be considered as an inactive globe. The eruptive processes from its surface will throw out the small pieces of nuclear substance which coming into the outside layer of the star will immediately disintegrate giving rise to the nuclei of different stable and radioactive elements.

We see thus that there are many different phenomena inside of a star giving rise to formation and transformation of different elements and the hope may be justified that further investigation will clarify the relative importance of various processes and lead to a complete explanation of the relative abundance of different elements in the universe.

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The Genetic System

This book is a radical departure from the usual genetics text. It is a careful, scholarly, point-by-point analysis of the materials and methods of genetics. One by one the assumptions and principles of heredity are held up to the light of scientific inspection, scrutinized, and evaluated. The formal logic, the one-two-three arrangement of points, and the insistent and almost exclusive use of Drosophila material, become almost monotonous by the time the reading of the volume is completed. One finds himself with the feeling that simple things have at times been made more difficult than necessary.

The distinction between heredity and the mechanism of heredity has been relegated to the past, and the author considers the facts and principles of inheritance under the broad heading of The Genetic System. The book is scantily illustrated, and the use of symbols for genes is far from consistent throughout the book. The mathematical implications of various systems of mating in populations, the question of equilibrium in populations, and their important corollary, the gene-frequency method, are not mentioned. An excellent chapter on the relation of characteristics to the environment provides a welcome break in the didactic presentation. The final two chapters, on chromosomal aberrations and mutations, respectively, are likewise warmer in tone and less painfully formal than the earlier chapters.

In the opinion of the reviewer, the book is unsuitable for an elementary text in genetics, but provides an excellent critique and a good lesson in logic for the more advanced student of genetics who wishes to review and "fix" his knowledge of the subject.—L. H. S.

Genetics, by H. S. Jennings. xiv+373 pp. New York, W. W. Norton & Co. 1935.

Vertebrates Through the Microscope

This volume presents a compact, concisely-written account of vertebrate histology, unique in that it is not centered around man and medical histology. System by system the microscopic anatomy of various forms is taken up on a descriptive basis. Widely varying vertebrate forms are used as examples, and the student is encouraged to discern the variations between the general descriptions given in the text and the specific form he may be studying at the time. The book is fully and excellently illustrated with diagrams and photomicrographs, mostly original. An excellent chapter on the blood cells presents clearly the differential classification based on the new supra-vital technique. Another very worth-while chapter is concerned with the histology of the endocrine glands. The final chapter is a concise outline of general histological technique. References accompany each chapter, with a general text reference at the end of the book.—L. H. S.

The Microscopic Anatomy of Vertebrates, by George G. Scott and James I. Kendall. 306 pp. Philadelphia, Lea and Febiger. 1935.

Pacemakers

This, the first of a proposed new series of monographs on experimental biology, deals with certain mechanisms underlying vital processes. The master reactions, or pacemakers, controlling the dynamic steady state, are presented and analyzed, as keys to the understanding of protoplasmic events. These are of the utmost importance to students of the behavior of living organisms, whether these students call themselves biochemists, biophysicists, physiologists, botanists, zoölogists, behaviorists, or psychologists. To bring out the central idea that a great deal of the overt behavior of organisms is determined by the interrelations of chemical events within cells and groups of cells quite independently of external environmental factors, the work of many investigators is presented and correlated. Chief among these are Osterhout and his colleagues, Parker, Crozier and their students, and the author and his own students. The various phenomena chosen as the basis for the correlated conclusions are permeability, growth, bioelectric effects, rhythmic activity, lateral line effects, sensory adaptation, and the physiology of the sense of time. The author is to be congratulated on bringing together in unified form such a series of interrelated phenomena. We wish success to this new series of monographs.—L. H. S.

Pacemakers in Relation to Aspects of Behavior, by Hudson Hoagland. x+138 pp. New York, the Macmillan Co. 1935.

How Good is Best?

The question of the range of human capacities and the comparative abilities of men becomes of importance in our present attempts at social reorganization. Are the seemingly great differences between men real or only apparent? The author of this unique volume concludes that the differences which separate the mass of mankind from one another are small, the ratios of the extremes of any given trait or ability, whenever measurable, falling within the limits of 1.3 and 2.5. The implications of this fact are discussed in detail. The point is made that genius represents only an added increment of qualities existent in all men, the increment at this point in the scale resulting in more profound changes than at others; much as an added degree of heat applied to water at 99° may profoundly change its characteristics, yet this added degree being no more of a quantitative increment than any other in the process of raising the water to a temperature of 99°. The raw data from which the conclusions of the book are drawn are given in full in appendices. It is quite certain that the responses of various readers of the volume will vary considerably in the degree of acceptance of the treatment and conclusions, yet it is imperative that the book be critically read by biologists, psychologists, sociologists, economists and statisticians.—L. H. S.

The Range of Human Capacities, by David Wechsler. ix+159 pp. Baltimore, the Williams and Wilkins Co. 1935.